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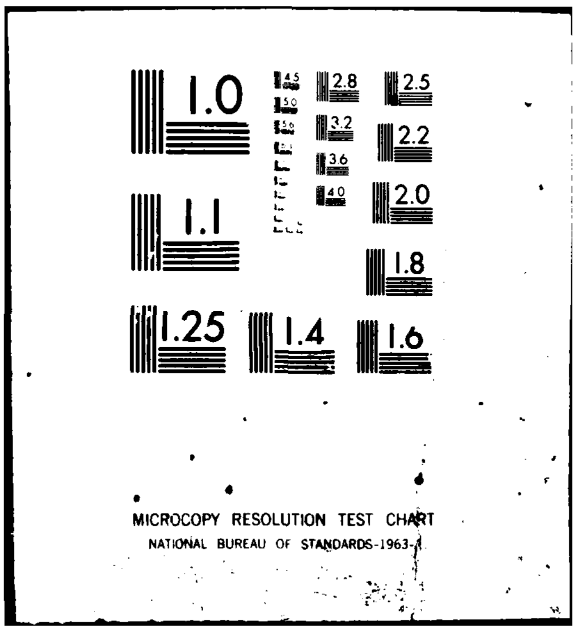
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LATERAL ROLLOVER PROTECTION CONCEPTS

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P.O. Box 482
Fort Worth, Tex. 76101

January 1980

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APPLIED TECHNOLOGY LABORATORY
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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report provides insight into the problem of lateral rollover during a helicopter accident. Design concepts for preventing the occurrence of a rollover accident are presented, as are concepts designed to minimize occupant injury and aircraft damage, should rollover occur. If a helicopter rolls over laterally, the ensuing damage from the main rotor striking the terrain ensures that the mission would be classified as an accident. The results of this contract will be used to improve helicopter design criteria and could be integrated into future research and development programs aimed at enhancing the flight safety and crashworthiness of Army aircraft.

Richard E. Bywaters and LeRoy T. Burrows of the Aeronautical Systems Division served as project engineers for this effort.

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Helicopter accidents in which the aircraft rolled over laterally are costly in aircraft damage. U.S. Army helicopter accident reports involving lateral rollover for a 6-1/2-year period were analyzed to determine their significant characteristics such that design concepts for rollover protection could be identified. The results of the accident analysis were applied to portions of crash survival specifications and design concepts for rollover protection. (Continued on reverse side)

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Dynamic rollover, when the aircraft is light on its landing gear, was investigated using computer simulation to identify pertinent parameters. A quick response from the pilot to reduce main rotor thrust is the primary means available for recovery. A preliminary evaluation of the KRASH computer simulation program was done for the rollover environment.

Design concepts that either prevented the occurrence of a rollover accident or minimized the dangers to the occupants as the aircraft rolled over were investigated. An automatic rollover sensing and correction system was investigated. Wing and wide landing gear concepts can provide increased rollover resistance. Means of preventing hazardous main rotor pylon motion during a rollover accident were also investigated.

PREFACE

This report covers the work accomplished from October 1977 to August 1979. The work described herein was performed under U.S. Army Contract DAAJ02-77-C-0078 and under the technical cognizance of Messrs. Richard E. Bywaters and LeRoy T. Burrows, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virgina.

This program was conducted at Bell Helicopter Textron (BHT). The principal investigator for this program was Mr. Roy G. Fox. Major contributors were Messrs. James D. Cronkhite, Victor L. Berry, Thomas J. Haas, David Popelka, and Larry L. Sheatsley, Jr.

A

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

1. INTRODUCTION

During a recent 6 1/2-year period, U.S. Army helicopter accidents involving a lateral rollover during the accident sequence have produced a monetary loss for aircraft equipment of 27 million dollars. A study was initiated to analyze these rollover accidents and to determine their significant characteristics such that design concepts for rollover protection could be identified.

2. ACCIDENT ANALYSIS

2.1 APPROACH

The approach used in the analysis of accident data was first to identify those U.S. Army helicopters that rolled over laterally. BHT requested all rollover accidents of U.S. Army helicopters be identified and the resulting data be provided by the U.S. Army Safety Center. Accident data was pulled by the Army Safety Center using their ABACUS accident retrieval system for the verb "rolled." Every model in the U.S. Army inventory except the Model CH-47 experienced a rollover accident. The monetary loss for aircraft equipment totaled $27,014,432 for 128 rollover accidents and was 12 percent of the total costs for all accidents for a 6 1/2-year period (1 July 1970 to 1 January 1977). The cost of rollover accidents during this period averaged $22.65 per flight hour for the Army helicopter fleet. The term "all accidents" used in this study includes every Army helicopter accident regardless of whether rollover occurred.

2.2 ANALYSIS

2.2.1 Rollover Accidents

If a helicopter rolls over laterally, the ensuing damage from the main rotor striking the terrain ensures that the mishap would be classified as an accident. For the 6-1/2-year study period, 128 U.S. Army helicopters rolled over, yielding an accident rate of 0.95 per 100,000 flight hours. Thus, the rollover accidents accounted for about 8.8 percent of all accidents.

The frequency of a rollover accident occurring for the models in the study is shown in Table 1.

TABLE 1. ROLLOVER ACCIDENT FREQUENCY
(1 July 1970 - 1 January 1977)

Model	Rollover Accidents	Rollover Accident Rate Per 100,000 Flight Hours
UH-1	54	0.75
OH-58	20	0.99
OH-6	10	1.59
TH-55	20	1.76
AH-1	17	1.94

Models eliminated from the detailed analysis due to a limited number of cases were: (1) Model CH-47, no reported cases; (2) Model CH-54, one case; (3) Model TH-13, two cases; and (4) Model OH-23, three cases. All other models had at least 10 cases. Twenty-four of the remaining accidents did not contain adequate details for analysis and were eliminated from the sample. Only one accident of the remaining sample was considered nonsurvivable (Model AH-1G free fall through tall trees) and was therefore removed from the sample. Thus, the remaining 97 rollover accidents for the 6-1/2-year period were selected for the detailed accident analysis to identify design concept needs for lateral rollover protection. The trends from these sample accidents with information should be applicable to most rollover accidents.

2.2.2 Injury Potential

A total of 259 fatal accidents occurred during this period. Only four of these 259 accidents, or 1.54 percent, involved rollover. Considering those accidents involving either major or fatal injuries, only 18 out of 1448 (1.2 percent) involved rollover. The percentage of major or fatal injuries incurred per the number onboard during an accident was 13.6 percent (45/330) for rollover accidents versus 23.4 percent (1204/5150) for all accidents. Therefore, it appears that the serious injury potential of a rollover accident is below that of an "average" accident.

2.2.3 Landing Gear Effects

Only one case (Model CH-54) of rollover occurred on a single main rotor helicopter with wheel landing gear. Therefore, it is not possible at this time to make any comparisons of wheels versus skids. The absence of wheeled helicopter rollover accidents should not be construed necessarily as a means of reducing the frequency of lateral rollover accidents, as the free motion of the main gear wheel is only in the forward or aft directions. Further study is needed after field experience with Models UH-60 and AH-64.

2.2.4 Flight Phase at Rollover

The flight phase of the aircraft for rollover accidents is shown in Figure 1. The takeoff phase accounted for 19.2 percent, a normal approach accounted for 44.3 percent, and true emergency autorotation accounted for 25.2 percent of the total rollover accidents. Apparently, this is related to the failure of the pilot to recognize, analyze, and respond properly to the situation. Visibility was not a factor.

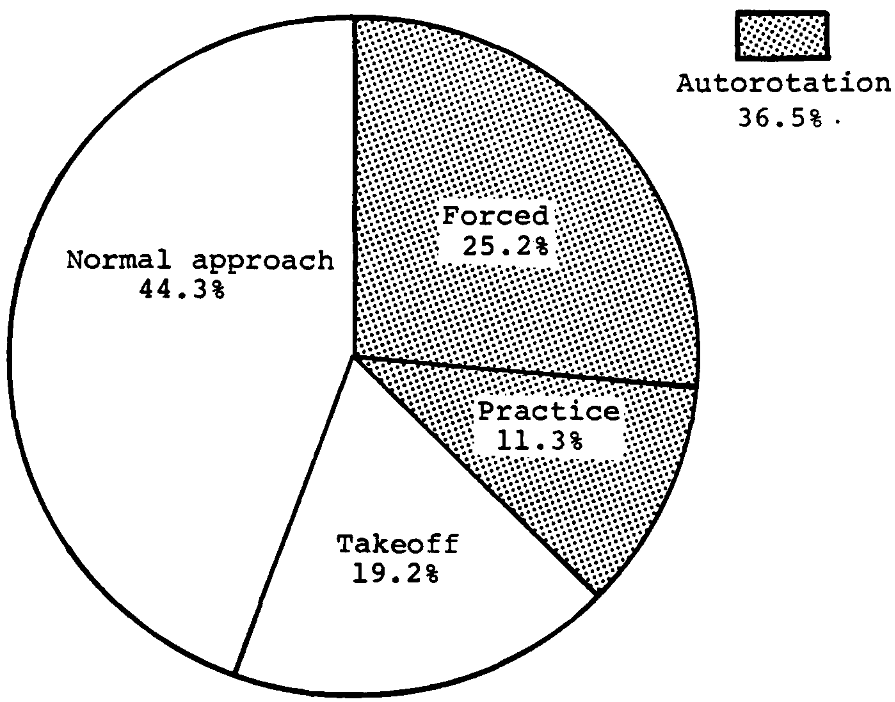

Figure 1. Flight phase at rollover.

Furthermore, most rollover accidents (85 percent) occurred during the daylight hours (as shown in Figure 2).

2.2.5 Terrain Effects

General terrain surfaces reported in the coded accident data are shown in Figure 3. Of the known terrain surfaces, it appears that the rollover accidents occurred on fairly hospitable landing sites. It is expected that sloping terrain would be a factor in a lateral rollover accident; however, accident data reported the ground appearance as sloping terrain in 20.6 percent of the accidents versus open and level in 66 percent of the accidents.

2.2.6 Initial Impact Conditions

2.2.6.1 Vertical Velocity

The reported vertical velocity at impact is shown in Figure 4. Vertical velocity is plotted at three points, due to the accident reporting technique. These data indicate that 88 percent of the cases experienced 10 feet/second (600 fpm) or less. Existing skid gear will generally accept up to 6 to 10 feet/second vertical sink speed prior to airframe ground contact.

2.2.6.2 Ground Speed

The reported ground speed is shown in Figure 5. The significance of this chart is that over 90 percent of the aircraft had a ground speed of 15 knots or less.

2.2.7 Configuration Effects

2.2.7.1 Helicopter Models

To better understand rollover accidents, it is necessary to look at the differences of aircraft configurations. Rollover accidents (as a percentage of all accidents) for each model are shown in Figure 6.

2.2.7.2 Direction of Roll

The tendency of aircraft to roll in one direction more than in the other was investigated. The OH-58A, OH-6A, and TH-55A helicopters, as a group, rolled over to the right as often as they did to the left (e.g., 22:22). The H-1 group (Models AH-1 and UH-1) did show a two-to-one tendency to roll over to the right as compared to the left (e.g., 33:17). This right-roll tendency may be related to the tail rotor being located high

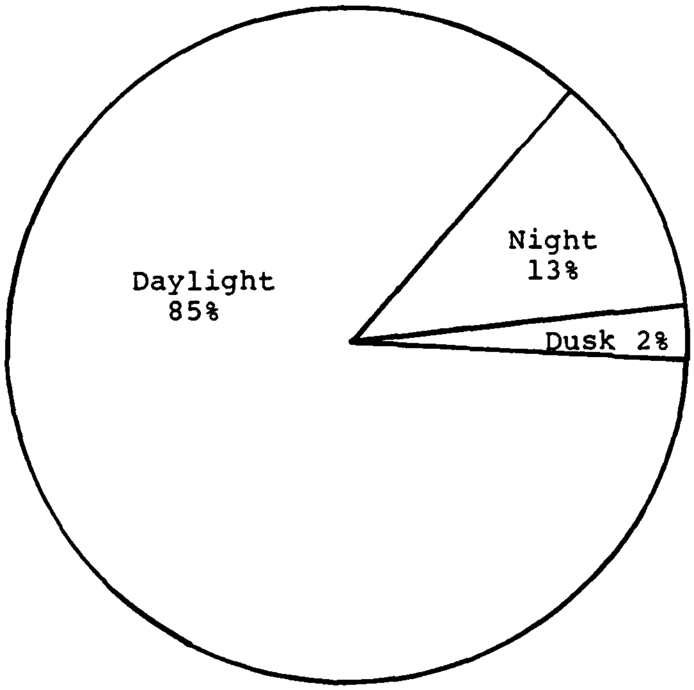

Figure 2. Period of day of rollover accidents.

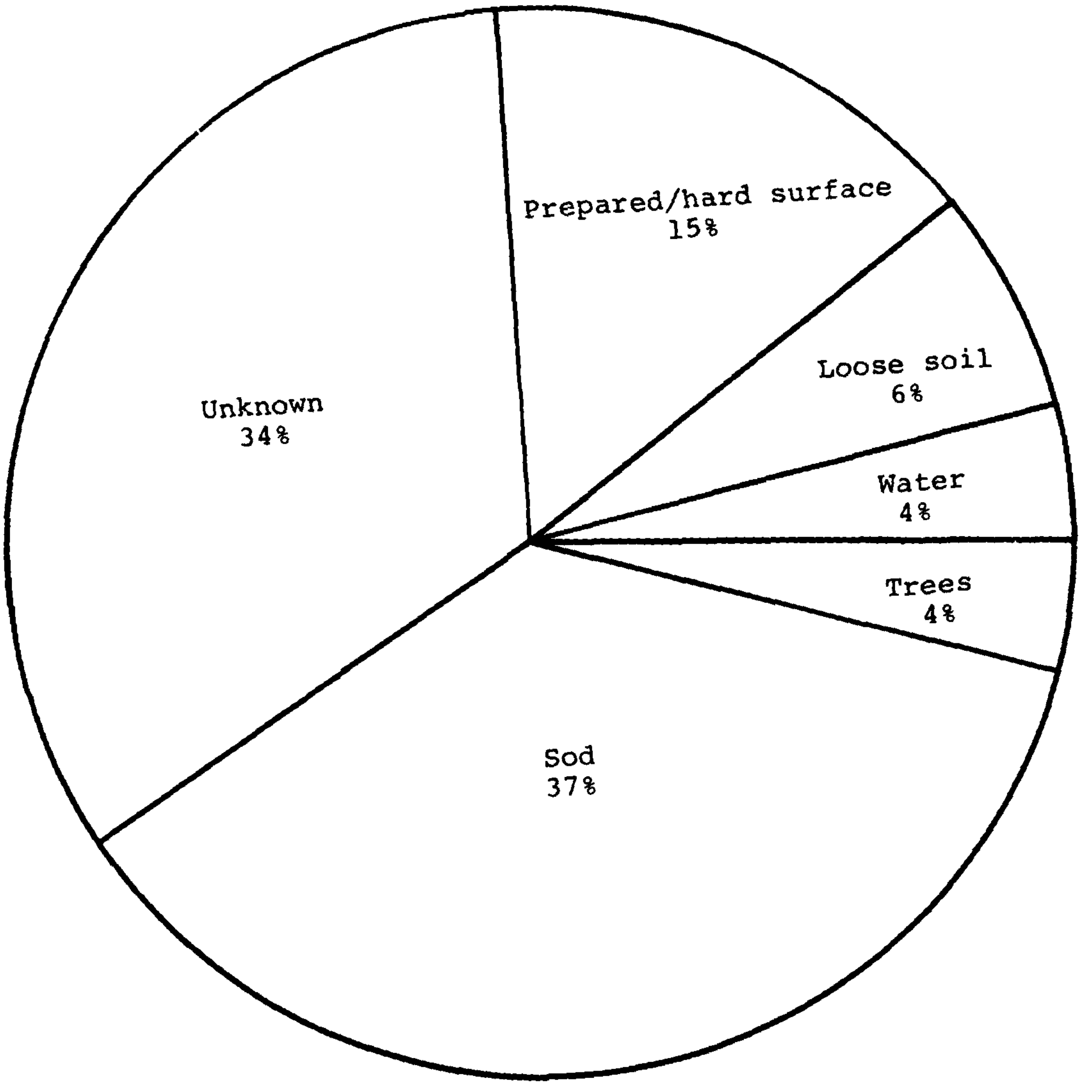

Figure 3. Terrain surface at rollover accident.

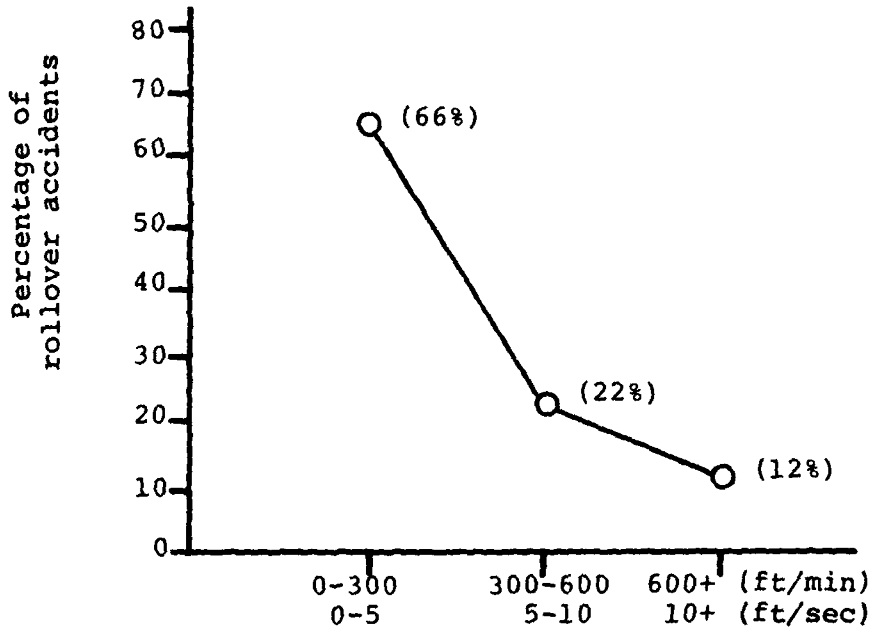

Figure 4. Vertical velocity of rollover accidents.

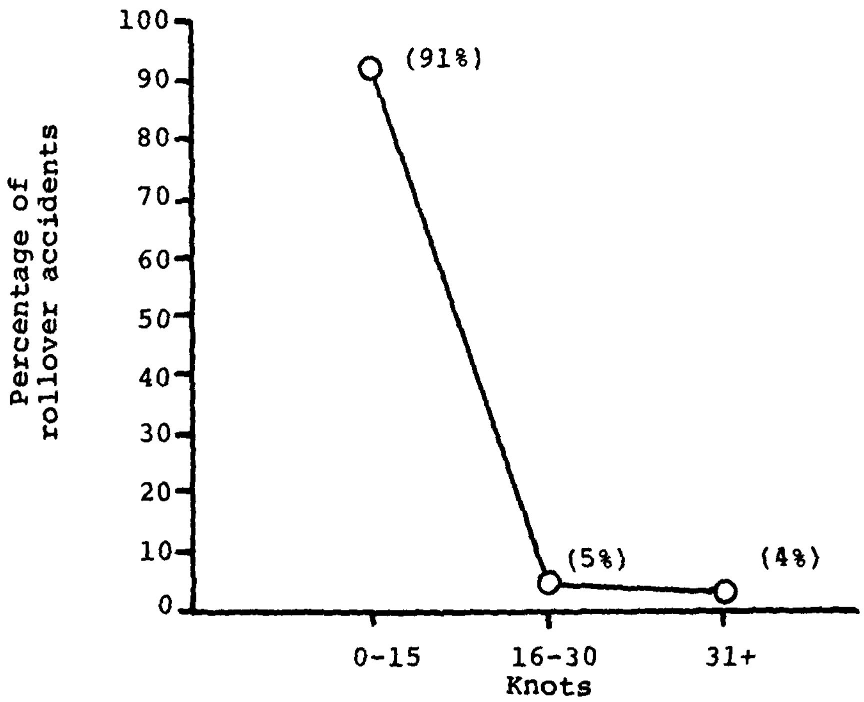

Figure 5. Ground speed of rollover accidents.

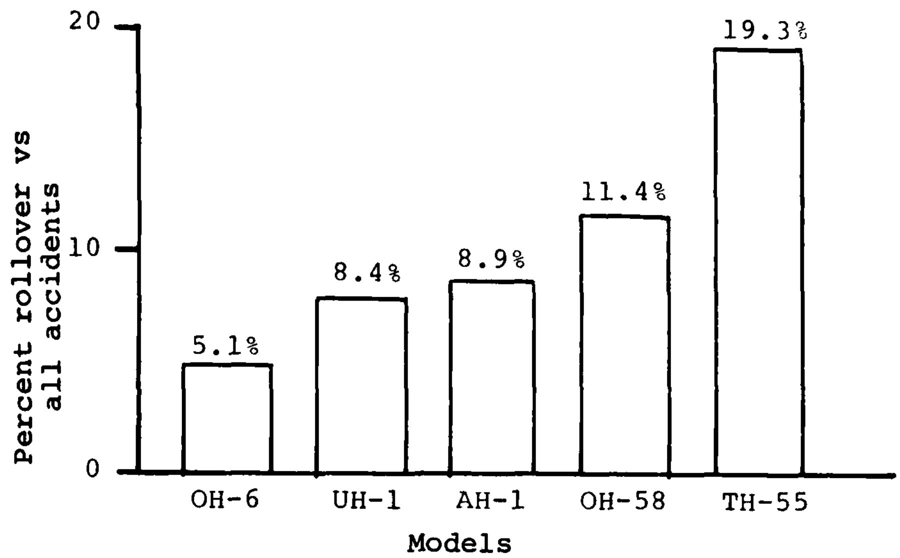

Figure 6. Percentage rollover by model.

above and further away from the aircraft center of gravity. The higher the tail rotor thrust axis, the more rolling moment must be controlled by the pilot during flight. In determining a tail rotor location, many variables such as antitorque requirements, aerodynamics, rotor wake, tail rotor strike potential, type landing gear, and operating environment must be considered. Regardless of tail rotor thrust axis location, the tail rotor thrust axis can vary from above to below the aircraft center of gravity during flight; thus, uncommanded roll tendencies will also vary accordingly.

2.2.7.3 Aircraft Weight

The distribution of rollover accident aircraft weights compared to the percentage of relative useful load range is shown in Figure 7. For example, Model UH-1H has an empty weight of 5200 pounds and a maximum gross weight of 9500 pounds. Thus, the relative useful load range is the difference between the minimum and maximum weights. Since each aircraft model has a different relative useful load, each data point must be considered as a percentage of its relative useful load range. A fairly consistent distribution of rollover accidents occurred throughout their relative useful load range, which indicates that the variance in the vertical aircraft center of gravity from different loadings is of little significance. The fleet average was 60 percent of the relative useful load range.

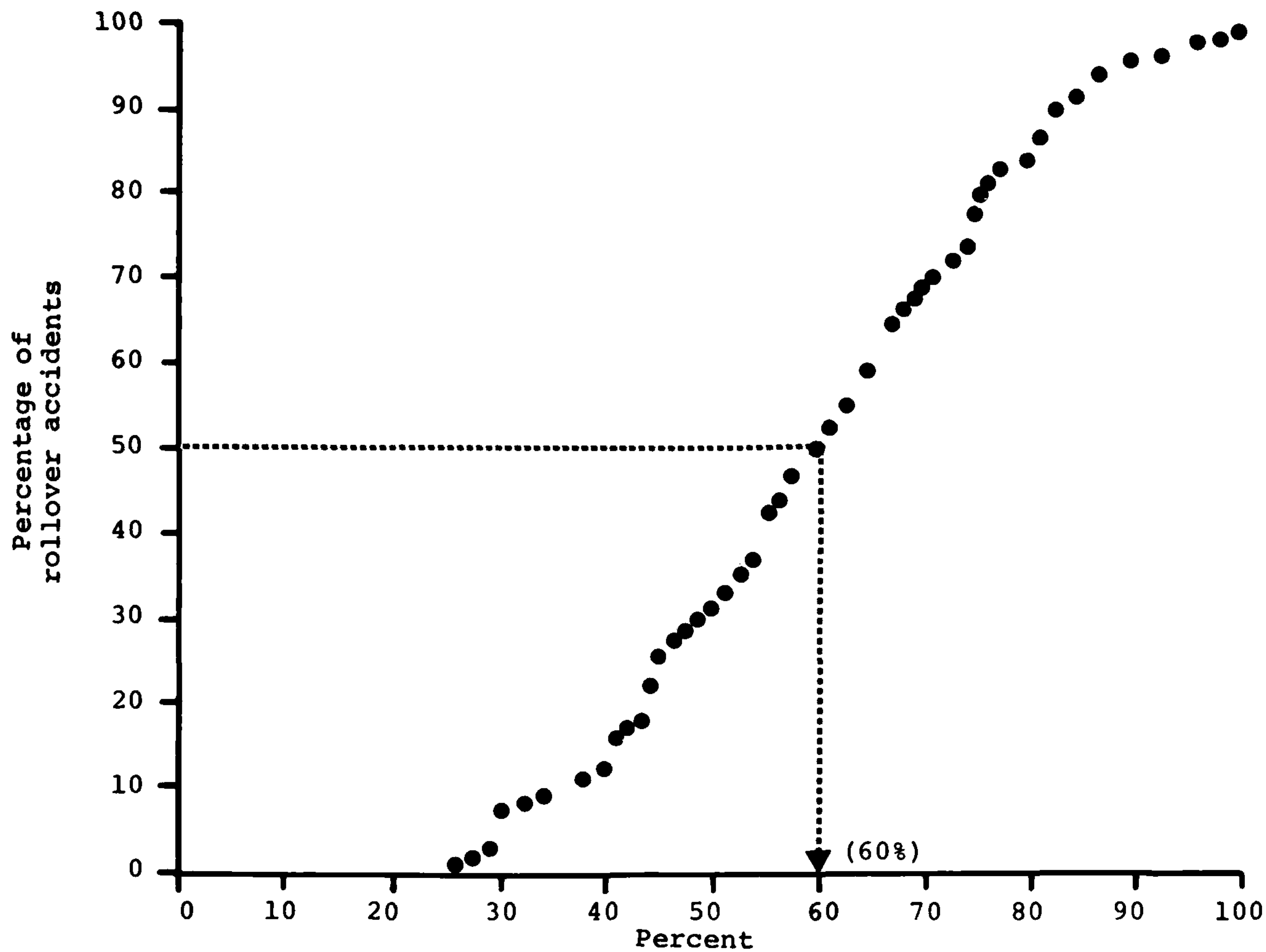

Figure 7. Percentage of relative useful load.

2.2.8 Rollover Accident Injuries

Major/fatal injuries accounted for 13.6 percent (45/330) of occupants onboard during rollover accidents. For all accidents during this period, 23.4 percent (1204/5150) of the occupants onboard received major/fatal injuries. Thus, the serious injury potential does not appear to be high in a rollover accident.

The known injury factors for major or fatal injuries are shown in Table 2.

TABLE 2. MAJOR OR FATAL INJURY FACTORS

Major/Fatal Injury Factor*	Number of Casualties		
	Fatal	Major	Fatal/Major
Deceleration forces	1	19	20
Cockpit	2	11	13
Struck by rotor	2	3	5
Burns	3	2	5
Thrown out of aircraft	1	3	4
Personal equipment (helmet)	1	3	4
Console, instrument panel		3	3
Seat belt/harness		3	3
Fixed controls	1	1	2
Seat		2	2
Troop compartment		1	1
Windshield, canopy		1	1
			63

* One person may receive more than one major injury.

Although injury factors may be grouped in many different combinations, grouping by potentially correctable areas indicates those areas needing improvement by priorities. This grouping is shown in Table 3.

TABLE 3. MAJOR/FATAL INJURY FACTORS

Injury Factor	Number of Casualties
Deceleration forces	20
Cockpit environment (controls, cockpit, console, instrument panel)	19
Retention system (seat, seat belt, harness, thrown out of aircraft, helmet)	13
Struck by rotor	5
Burns	5
Troop compartment	1
	63

Major areas for potential improvement are deceleration forces, the cockpit, occupant retention system, and rotor strike. The troop compartment does not need improvement in regard to rollover accidents. Postcrash fire protection has been improved by the introduction of crash-resistant fuel systems. It should be noted that poor restraint system performance is directly related to striking items in the cockpit environment.

2.2.8.1 Injuries by Seat Location

The major or fatal injuries that occurred by seat location in rollover accidents are shown in Table 4. Models AH-1 and TH-55 are not applicable to this table as the subject being investigated is the effects due to cockpit versus cabin seating.

TABLE 4. CASUALTY SEAT LOCATION FOR MAJOR/FATAL INJURIES

Seat Location	Number of Casualties	Total Number Onboard	Percent Casualties Onboard
Pilot	14	70	20
Copilot	12	56	21.4
Troop	16	123	13

The resulting percentages of major or fatal injury of 20 and 21.4 percent in the crew positions (pilot and copilot, respectively) are higher than the troop compartment seat percentage (13 percent). This further substantiates the grouping of areas of improvement previously discussed in Paragraph 2.2.8.

2.2.8.2 Injuries due to High Mass Items

Although the rotor blades struck the ground during every rollover accident, very few serious injuries resulted from high mass item displacements. In only one case was a transmission reported as displaced into the cabin; however, the cabin was not occupied and no injury resulted. The main rotor blade did penetrate the cockpit in four accidents and caused five major or fatal injuries. In all four cases, the main rotor had previously separated from the aircraft during the ground striking sequence. Furthermore, all injured by the blade intrusion were sitting on the left side of the aircraft.

2.2.9 Escape/Egress

2.2.9.1 Exits Used

The means by which the occupants escaped the rollover aircraft were investigated. Approximately 39 percent of the occupants reported using the normal exits; only 5 percent reported using the emergency exits. More than one-half (56 percent) reported using other than normal or emergency exits. The other exits were primarily a broken windshield or overhead transparency.

2.2.9.2 Difficulties Encountered

The emergency evacuation difficulties reported are shown in Table 5. Ninety-six occupants reported no difficulty in getting out of the aircraft. The most prominent difficulty reported was reaching the exit due to the aircraft's attitude at rest.

TABLE 5. DIFFICULTIES ENCOUNTERED DURING ESCAPE

Difficulty *	Number of Occurrences	Percent of Occurrences
Reaching exit due to aircraft attitude	82	53.9
Hampered by injuries	27	17.5
Door would not open	26	16.9
Hampered by airframe structure	16	10.4
Hampered by personal effects	2	1.3
Hampered by other occupants	1	.6

*Each occupant may have more than one difficulty.

2.2.10 Pylon Displacement

Displacement of the main rotor pylon was investigated. Two of the basic factors involve the structural strength of the transmission and the effects of blade strikes.

2.2.10.1 Transmission

Crash load factors are indicative of strength during static loading, but they may not be applicable during a dynamic loading. For example, the TH-55 has a very low static crash load factor, but the transmission remained in place in most cases. The Model AH-1, with considerably higher static crash load factors, had transmission displacements in many cases. The important difference between the Model TH-55 and the Model AH-1 is the blade strike loading that is experienced by the transmission. Model TH-55 has a fully articulated main rotor hub. This configuration apparently permits the main rotor blades to destroy themselves without transferring excessively high crash loads to the transmission. Model AH-1 has relatively high inertia rotor blades on a semirigid, teetering main rotor hub. The large main rotor inertia gives the pilot some additional margin during a powerless autorotation and thus reduces the frequency and severity of accidents and incidents. However, the high inertia can be detrimental during a rollover crash when the blade strikes the terrain. More kinetic energy (rotor blade inertia) must therefore be dissipated during the rotor strikes.

The potential different direction of transmission displacement due to rolling onto the left side versus the right side was also investigated. The primary direction of the transmission displacement was observed where possible from the accident photographs. No strong correlation was noted, but the tendency was more prevalent for the transmission to displace forward when the aircraft rolled over to the left, and to displace left when the aircraft rolled over to the right.

2.2.10.2 Main Rotor Effects

Different blade strike effects were observed due to the type of main rotor installed. The semirigid teetering rotor is installed on about three out of four U.S. Army helicopters and was thus studied in more detail. The hub and blade assembly is extremely rigid in the plane of rotation, but it can easily flap up and down as a unit. If mast separation occurred during ground strikes, the main rotor hub and blade assembly remained basically intact after leaving the aircraft. If the blade tip dug into the terrain, separation within the blade occurred. Model OH-6 and TH-55 main rotors are fully articulated, thus some motion in the plane of the blade disc and in flapping is allowed during normal operation. The articulated rotor blades either folded up in the upward flapping direction, deformed aft, or were totally disintegrated, leaving portions of the blade. Figure 8 of a Model TH-55 shows one completely separated blade and two blades that deformed aft. The articulated rotor hub generally stayed in place.

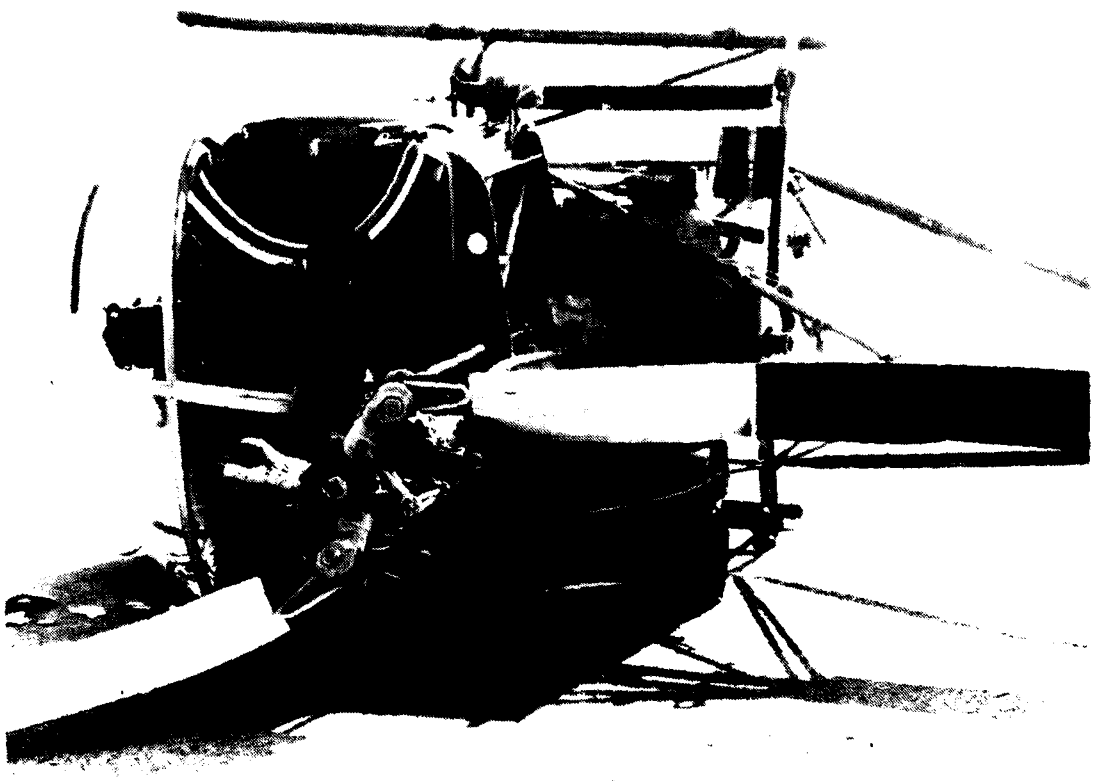

Figure 8. Blade damage on fully articulated main rotor.

2.2.11 Crash Kinematics

Since about three-fourths of the aircraft in the U.S. Army rotary wing fleet have a teetering rotor, its expected kinematics due to the blade strikes were theorized.

The kinematics of the pylon during a rollover to the right are believed to follow this basic sequence:

- Main rotor blade tip strikes the terrain a glancing blow that forces the main rotor blade to flap up such that the main rotor hub is forced against the flapping stops.

- The other main rotor blade tip then strikes the terrain another glancing blow and also forces excessive blade flapping with resulting mast damage at the main rotor hub flapping stops.

- During both of these blade strikes, the transmission is severely loaded such that the transmission is being pushed out to its left side. Transmission strength in its case or its mounting may be exceeded at this point.

- With severe mast damage at the flapping stops, the main rotor hub and blades may separate as a unit from the mast and literally fly by itself. With no control of the rotor, the potential is now present for a blade penetration into the cockpit. In some cases, part of the transmission case may fly away with the rotor.

- The transmission and/or its mounting structure, being previously damaged by the excessive hub flapping, is now displaced to the left as the aircraft rolls over toward its roof.

Note: If the blade digs in (i.e., stops suddenly) instead of suffering only a glancing blow, the damaging loading is transmitted in the rotor disc plane to the mast, transmission, and transmission mounting.

Based on this sequence of events, the methods of providing better occupant protection during rollover should include:

- Minimize excessive flapping damage and loading between blade tip and the mast.

- Minimize transmission case and mount loading.

- Increase structural strength in certain areas.

2.2.12 Livable Volume Retention

A livable volume around the occupants must be maintained during a crash if the crash is to be survivable. Review of available photographs indicated that the livable volume was reduced in a total of 19 cases, as shown in Table 6. However, in only four of those 19 cases was the livable volume reduced significantly to cause a severe injury. In all four accidents, the main rotor had previously separated from the aircraft structure and had struck occupants sitting on the left side of the aircraft.

TABLE 6. LIVABLE VOLUME REDUCTION

Model	Severe Reduction	All Occurrences
AH-1	-	-
UH-1	1	6
OH-58	3	7
OH-6	-	4
TH-55	-	2
Total	4	19

Livable volume reduction occurred in all models studied except the Model AH-1. This is especially interesting as the Model AH-1 has a transparent canopy overhead in lieu of a roof structure. The "stub wings" of Model AH-1 protect the canopy and its occupants. The final resting attitude of the Model AH-1 was always in one of three side positions (Figure 9). In all cases, a wing tip was on the ground and thus prevented the canopy side from severely impacting the terrain. In some of the inverted positions, the canopy corner appeared to be just resting on the ground, but the canopy was still intact as shown in Figure 10. Furthermore, the structure around the transmission and above the canopy prevented severe canopy deformation. This condition was true regardless of whether the transmission or tail boom was separated from the fuselage.

For all cases except one, the livable volume reduction was always in the cockpit area for all models. The effects of livable volume reduction could not be directly correlated to

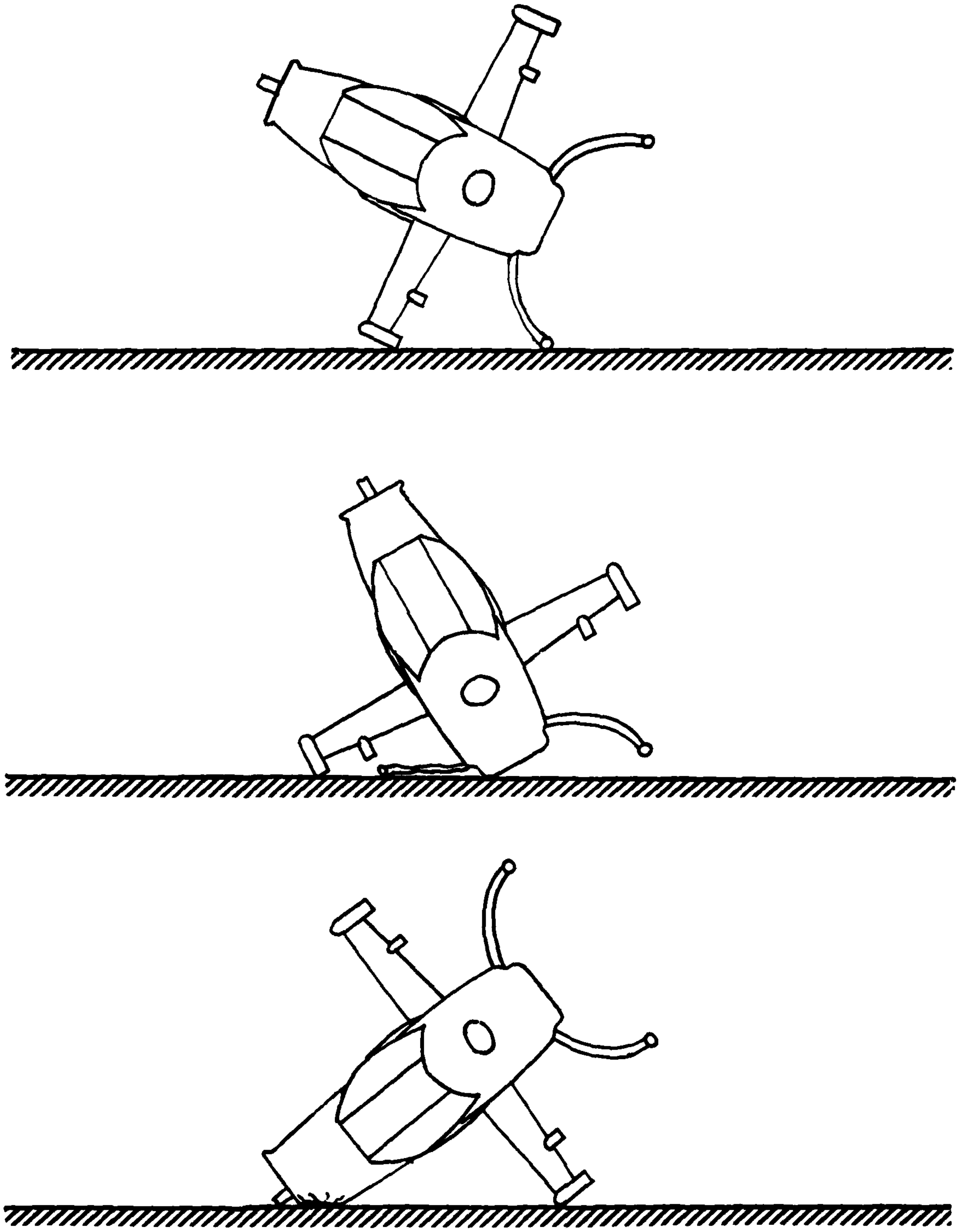

Figure 9. Model AH-1 resting attitudes.

Figure 10. Model AH-1 inverted resting attitude.

the injuries, except in the four cases of main rotor blade penetration. Some aircraft cockpits appeared to have only minor volume loss, whereas others had major volume loss. Obviously, a rollover in rocky terrain can result in localized livable volume losses, but this was not the general case.

3. DESIGN CRITERIA REVIEW

Existing design criteria of MIL-STD-1290 (Reference 1) and TR 71-22 (Reference 2) that are applicable to a rollover accident were reviewed and compared with the results of the accident data analysis. Only proposed changes are included in this section. The appropriate existing paragraph is typed with deletions noted by marking through or crosshatching (/////) the applicable portions. Additions are indicated by an underline (_______).

3.1 MIL-STD-1290

Applicable paragraphs of MIL-STD-1290 were reviewed to determine if changes were needed. Only those paragraphs applicable to possible revision are addressed below. The rationale for each revision follows its respective paragraph.

> 5.1.1.1 Impact conditions - The contractor shall demonstrate analytically that the basic airframe is capable of impacting longitudinally into a rigid abutment or wall at a contact velocity of 15 ft/sec without crushing the pilot and copilot stations to an extent which would either preclude pilot and copilot evacuation of the aircraft or otherwise be hazardous to the life of the aircraft occupants. For this impact, the engine(s), transmission, and rotor system for Type II aircraft shall remain intact and in place in the aircraft except the rotor blades. The basic airframe's capability to impact longitudinally into a rigid abutment or wall at a contact velocity of 40 ft/sec without reducing the length of the passenger/troop compartment by more than 15 percent shall be demonstrated analytically. Any consequent inward buckling of walls, floor, and/or roof shall not be hazardous to the occupants and/or restrict their evacuation. The aircraft shall also be designed to withstand impact as in low angle, missed approach. The impact conditions of this type accident are illustrated in Figure 19 (see Appendix). These impact conditions in plowed soil can ~~will more than likely~~ result in a rollover, and rollovers

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[1]Military Standard, MIL-STD-1290, LIGHT FIXED- AND ROTARY-WING AIRCRAFT CRASHWORTHINESS, Department of Defense, Washington, D. C., 25 January 1974.

[2]Turnbow, J. W., et al., CRASH SURVIVAL DESIGN GUIDE, Dynamic Science, Division of Marshall Industries; Technical Report 71-22, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, October 1971, AD 733358.

can be ~~are~~ critical for inward crushing and/or separation of the fuselage as shown by past accident experience. The volume of the cockpit for the occupied passenger/troop compartment shall not be reduced by more than 15% (5% desired) for the conditions indicated. Should the aircraft turn over under these conditions, the fuselage container should maintain structural integrity for a minimum of two 360° rolls. The static loads to be considered for rollover analysis are specified in Paragraph 5.1.4.

RATIONALE:

The analysis of rollover accident data in Section 2 can not substantiate this statement but does indicate a less severe crash environment. It is believed that the accidents previously used in establishing these criteria had more severe impact conditions than the accidents used in this rollover study.

5.1.4 Rollover impacts - The aircraft shall be designed to resist an earth impact loading as occurs when the aircraft strikes the ground in either a 90-degree (sideward) or 180-degree (inverted) attitude. The contractor shall analytically demonstrate that a rollover accident shall not cause an injury due to structural intrusion into the occupied volume. Unless otherwise specified, assume that the forward fuselage roof is buried to a depth of 2.0 inches in soil for the inverted attitude and that the load is uniformly distributed over the forward 25 percent of fuselage occupied length. Assume that the fuselage side is buried to a depth of 2.0 inches in soil for the sideward attitude and that the load is uniformly distributed over the forward 25 percent of fuselage occupied length. The fuselage shall sustain a 4G (i.e., 4.0 x aircraft basic structural design gross weight) load applied over the area(s) described for either the inverted or sideward attitudes shown in Figures 20a and 20b respectively, without permitting sufficient deformation to cause injury to seated, restrained occupants. For both cases in Figure 20, the 4G distributed load shall be analyzed for any angle of load application ranging from perpendicular to the fuselage skin (i.e., compressive loading) to parallel to the fuselage skin (i.e., shear loading). When designing for this condition, assume that all doors, hatches, and similar openings cannot carry any loading. The basic fuselage structure with rotor pylon(s) shall be considered to be intact.

RATIONALE:

Analytical simulation should be used to show the rollover protection capability of the aircraft structure. When accurate rollover conditions are obtained (such as from flight/crash data recorders), then specific rollover criteria can be established and incorporated into MIL-STD-1290. The beneficial wing effects on AH-1 accidents suggest a possible clarification is needed. Since (1) aircraft transparent canopies cannot support high roof loads when inverted except at the canopy frame, and (2) wings prevent canopy side contact, it appears that different criteria should apply to winged helicopters with full canopies. Furthermore, the present requirement does not specify the aircraft damage condition relative to pylon or tailboom attachment.

5.1.7.2 Type II aircraft - Transmissions and rotor masts shall be designed to prevent potentially hazardous displacement or tilting under the crash conditions cited in 4.2. The contractor shall analytically demonstrate that the transmission, rotor mast, rotor hub, and rotor blades will not displace in a manner hazardous to the occupants during the following impact conditions:

a. Rollover about the vehicle's x or y axis on sod.

b. Advancing and retreating blade obstacle strikes that occur within the outer 10 percent of blade span assuming the obstacle to be an 8-inch-diameter rigid cylinder.

Prevention of hazardous displacement of dynamic components shall take precedence over ultimate (static) load factors. Unless otherwise specified, all mass items that would pose a hazard to personnel during a crash shall be designed to withstand the following ultimate load factors:

a. Applied Separately

Longitudinal	±20
Vertical	20/-10
Lateral	±18

b. Applied Simultaneously

Longitudinal	±20	±10	±10
Vertical	10/-5	20/-10	10/-5
Lateral	0	±9	±18

RATIONALE:

These static load factors may be too high or too low depending on many aircraft configuration features. The important point is to prevent the occupant from being injured rather than preventing component displacement. Some component displacement is helpful in absorbing crash load rather than transferring those loads to another area.

5.1.8 Shape of Fuselage Cross Section - The shape of the fuselage has an inherent influence on the inward load-deformation properties of the fuselage. Both crash test experience and accident analysis indicate that an ellipsoid-shaped fuselage is optimum. A cylindrical cross section inherently provides a curved surface to resist inward crushing. In addition, an ellipsoidal fuselage will result in lower "rollover" loads than would a flat-sided fuselage under identical conditions. However, disregarding the effects of the landing gear, an ellipsoidal fuselage has less resistance to rolling over when compared to a rectangular fuselage. Crushable materials can be provided at the lower fuselage corners of a rectangular fuselage to resist rollover and to reduce crash loads during near-vertical (±30°) impacts. ~~Even though operational considerations will prevent the use of an exact ellipsoid-shaped fuselage, an approach to this shape is a worthwhile design goal~~.

RATIONALE:

Historically, a cylindrical fuselage has provided more inherent resistance to inward crushing than a rectangular shape for aircraft designed only to airworthiness requirements (e.g., no consideration for the severe crash). However, aircraft structures designed to MIL-STD-1290 criteria can have equivalent inward buckling resistance, regardless of rectangular or circular cross sections. The rectangular shape is generally more effective in maximizing internal volume use and minimizing external fuselage size for airplane transportability. Furthermore, there is less resistance to rollover from a circular fuselage (disregarding landing gear effects) than with a rectangular fuselage. Analysis of 115 survivable Model UH-1D/H accidents from 1 January 1972 to 30 September 1976 shows the aircraft roll attitude at time of major impact (Figure 11). These data indicate that there are more accidents in the 6- to 45-degree roll attitude range than in the 60- to 90-degree range. A rectangular-shaped fuselage with crushable material in the lower outboard corners could attenuate crash loads in the 6- to 45-degree range where protection is most needed.

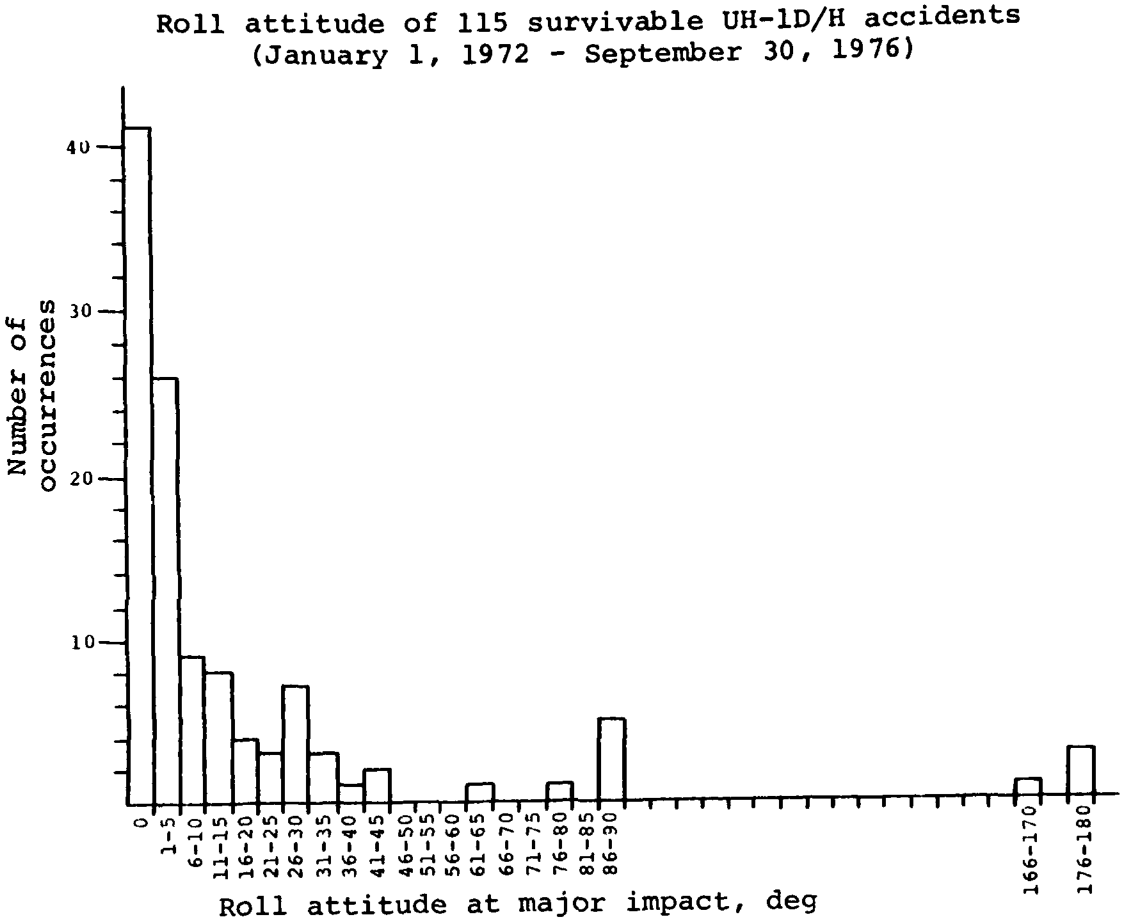

Figure 11. Roll attitude at major impact.

5.2.3.1 Head impact protection - Because the head is the most vulnerable part of the body, it should be afforded maximum protection. Head impact tolerance is defined in USAAMRDL TR 71-22. Clearance of at least (?) inches above a 95th percentile man's head shall be provided in all seat locations. Design of the head strike envelope shall incorporate the following protective features:

RATIONALE:

The head strike envelope given in TR 71-22 is based on forward and lateral loadings, not vertical (eyeballs up), which is applicable during a rollover accident. Technical Report 71-22 notes 4 inches of torso forward movement away from the seat back with only 4G acceleration. The amount of restraint slack or elongation, body compression, or neck extension in the eyeballs-up direction is not known; thus, a more operationally suitable head clearance distance cannot be determined at this time.

3.2 USAAMRDL TR 71-22

Applicable paragraphs of TR 71-22 were reviewed to determine if changes were needed. Only those paragraphs applicable to possible revision are addressed below. The rationale for each revision follows its respective paragraph.

2.7.1 General - The shape of the fuselage has an inherent influence on all these methods except c. Rectangular cross sections can be designed to provide the same crashworthy characteristics as spherically, cylindrically, or elliptically shaped fuselages. ~~However, in practice they are not.~~ The circular or elliptcal cross sections normally result in stronger structures. Also, the cavities between curved fuselage skin and flat floors or essentially flat inner walls provide volume for the inclusion of energy-absorbing material. The result has been that curved fuselage configurations of aircraft designed only to airworthiness requirements were ~~are~~ generally more crashworthy than rectangular ones. However, disregarding the effects of landing gear, a circular-shaped fuselage has less resistance to rolling over when compared to a rectangular fuselage. Crushable materials can be provided at the lower fuselage corners of a rectangular fuselage to resist rollover and to reduce crash loads during near-vertical (±30 degrees) impacts.

RATIONALE:

The rationale was given previously for Paragraph 5.1.8 of MIL-STD-1290.

2.10 DESIGN OF ENGINE MOUNTS AND STRUCTURAL SUPPORT OF OVERHEAD MASSES

The strength of engine and its mounts and fittings should be such that failure or separation of the major structural members supporting the engines occurs before engine mount failure under any anticipated crash conditions. Structural support of massive components located overhead, such as the transmission and rotor mast on helicopters, should be designed such that these components do not penetrate occupied areas and injure the occupants during a crash. The protection required should either be substantiated analytically or by designing to the following ultimate (static) crash load factors: ~~to withstand the following loads, lateral, 18G, longitudinal, 20G, and vertical, 20G. These strengths are necessary to assure that overhead components do not penetrate the occupants' protective shell.~~

a. Applied Separately

Longitudinal	±20
Vertical	20/-10
Lateral	±18

b. Applied Simultaneously

Longitudinal	±20	±10	±10
Vertical	10/-5	20/-10	10/-5
Lateral	±0	±9	±18

RATIONALE:

The rationale was presented previously for Paragraph 5.1.7.2 of MIL-STD-1290.

4. ROLLLOVER SIMULATION ANALYSES

4.1 APPROACH

This section describes the analytical methods that were used during the program to simulate the rollover response of the helicopter. The results of the accident data analysis described in Section 2.2 indicated that rollover accidents associated with dynamic rollover conditions predominated over crash-impact type of conditions. Therefore, much of the analysis was oriented to dynamic rollover simulation that involves helicopter rigid body characteristics, main and tail rotor thrust, cyclic, gravity, ground slope, etc., rather than the nonlinear crash impact response of the helicopter structure. Pertinent references that were found relating to dynamic rollover are summarized in Section 4.2. A dynamic rollover analysis procedure that was used to evaluate parameters affecting rollover is described in Section 4.3 along with analytical results. In Section 4.4, analyses using simplified and detailed KRASH structure crash simulations and the NASTRAN structure analysis programs were conducted in order to evaluate the use of these two methods for simulating airframe structure rollover response due to crash impact, plus rotor response and pylon loads due to in-plane blade strike.

4.2 LITERATURE SURVEY

A literature search on dynamic rollover was conducted by reviewing available journals and magazines and by using a computerized library search system. The computerized search was done using the National Technical Information Service (NTIS) data base that accesses engineering reports, standards, and books. A set of nine useful papers (References 3 through 11) were obtained from this search. Highlights of these papers are summarized in the following paragraphs. References 5, 9, 10, and 11 describe the factors affecting dynamic rollover. These references can be briefly summarized as follows:

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[3]Buchan, M., MAIN ROTOR UP, U. S. Army Aviation Digest, October 1977.

[4]Buchan, M., and Lambert, A. R., ROLLOVER! TILT! UPSET!, U. S. Army Aviation Digest, May 1973, pp. 44-47.

[5]Cress, Capt. J. P., DONE IN: DYNAMICALLY, Approach, May 1975, pp. 12-14.

[6]Kelley, Bartran, PILOTS SHOULD BE CAREFUL WHEN LIFTING OFF, HOVERING, Rotor Breeze, February 1970.

- Dynamic rollover is caused by developing excessive angular momentum about a wheel or skid.

- The aircraft moment of inertia about a skid or wheel is generally four to eight times higher than that about the aircraft center of gravity (cg).

- The roll rates that precipitate dynamic rollover are generally similar to those experienced in normal flight conditions.

- Increased main rotor thrust aggravates the dynamic rollover problem and thrust reduction is a powerful means of controlling rollover.

- The helicopter weight produces the primary stabilizing moment for dynamic rollover.

- Two other measures of rollover characteristics, involving static considerations only, are:

    - Static rollover angle - power-off slope angle at which helicopter cg exceeds the landing gear and thus rolls over due to weight.

    - Critical rollover angle - maximum trimmable slope angle with full corrective lateral cyclic applied.

- Dynamic rollover can occur within 2 seconds.

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[7]Manningham, Dan, AIR-GROUND TRANSITION: HELICOPTER'S MR. IN-BETWEEN, Buiness and Commercial Aviation, January 1979, pp. 52-54.

[8]Roth, Barney, TILT...HOW TO MAKE SLOPE LANDINGS AND TAKEOFFS IN SINGLE ROTOR HELICOPTERS, U. S. Army Aviation Digest, July 1965, p. 20.

[9]Saunders, G. H., DYNAMIC ROLLOVER, Rotor and Wing, November 1976.

[10]Zody, Major J.W., BEST WAY TO DESCRIBE DYNAMIC ROLLOVER... FIRST DESCRIBE WHAT IT IS NOT, Safety Sentinel, August 1977.

[11]HELICOPTER CONTROL DATA AND CRITICAL ROLLOVER ANGLE, Department of the Air Force, Washington, D. C., 18 January 1971.

- The pilot is a major factor in dynamic rollover.

The rollover avoidance procedures are described in References 3, 4, 6, 7 and 8. These references can be summarized as follows:

- Perform ground maneuvers smoothly. Do not allow roll rates to increase. Avoid jump takeoffs.

- Maintain skid level during takeoff and landing. Do not allow uphill skid to leave the ground first during lift-off.

- Keep aircraft trimmed laterally during ground contact.

- If lateral control appears sluggish, reduce collective and check for obstructions.

- To correct roll rate, reduce collective smoothly. Avoid fast collective drop to prevent blade strike or fuselage bounce.

- Check crosswinds and lateral center-of-gravity offset.

4.3 DYNAMIC ROLLOVER ANALYSIS

4.3.1 Approach

A simplified analytical model was constructed to study dynamic rollover. This model was used to develop general trends for the various factors that affect dynamic rollover. Since there are an infinite set of possible rollover conditions and pilot control inputs, the approach taken was to vary each factor separately while holding the other factors constant. Although this may not represent an actual rollover situation, the influence of the various factors is easily evaluated by comparing it to a baseline condition.

4.3.2 Math Model

A simple, two-dimensional, single-degree-of-freedom math model was developed to investigate dynamic rollover. The math model is illustrated in Figure 12. The following assumptions were made in this analysis.

- Rigid body helicopter pivots about one skid, starting from an initial roll angle, ϕ, with roll rate, $\dot{\phi}$, on a ground slope, θ. There is no skid flexibility or slipping on the ground.

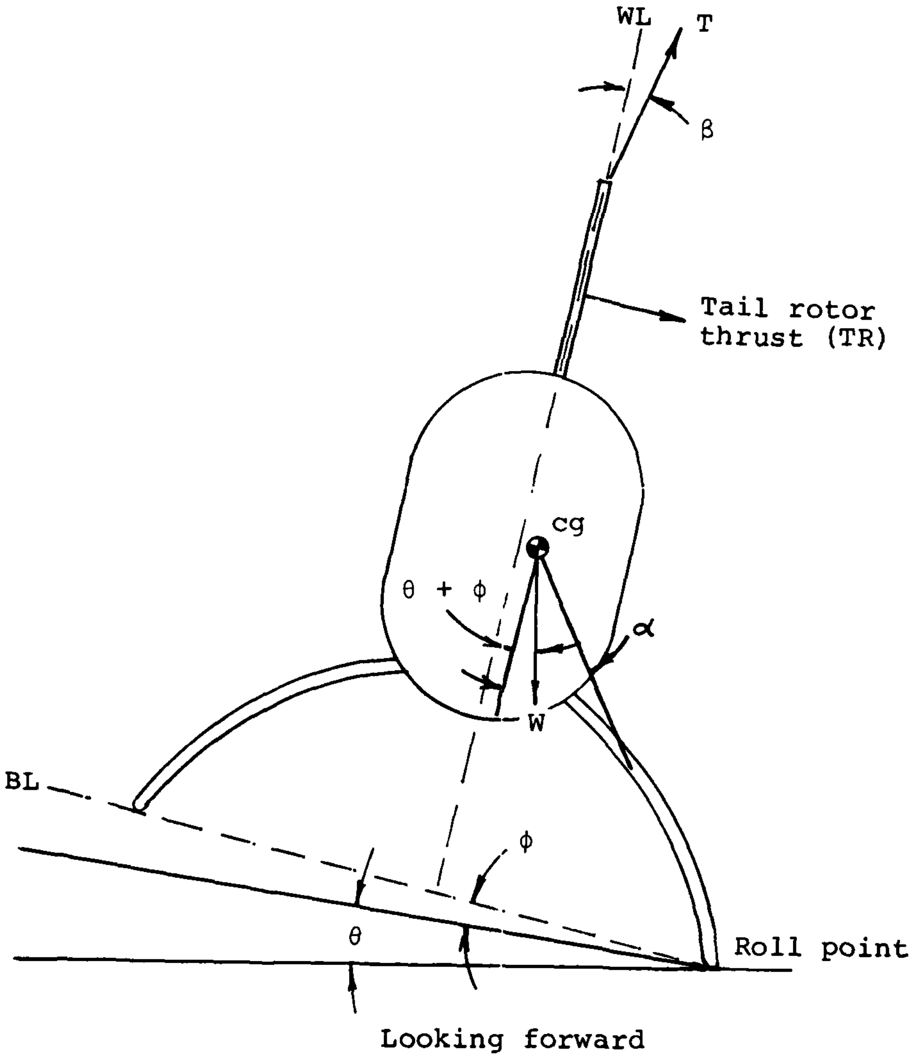


Figure 12. Mathematical model for dynamic rollover.

- Fuselage is represented by the mass and inertia properties at the center of gravity.

- The main rotor thrust vector, T, acts at the top of the mast at an angle β. The thrust, T, and angle β can be varied as a function of time.

- The tail rotor thrust, TR, acts perpendicular to the fuselage vertical axis. The tail rotor thrust can be varied as a function of time.

- Rotor control response lag and rotor damping moments are not modeled.

The math model was used to study the effect of several factors on the rollover characteristics of a helicopter. The factors chosen for the investigation were:

- Initial roll rate

- Ground slope

- Tail rotor thrust

- Main rotor lateral cyclic

- Main rotor collective

4.3.3 Baseline Configuration

A utility helicopter was selected as the baseline configuration for all analyses and is summarized below:

- Gross weight (gw) = 9274 pounds

- Main rotor lift = weight (e.g., no collective movement by pilot and aircraft light on landing gear)

- Tail rotor thrust balances mast torque (e.g., no pedal movement by pilot)

- Main rotor lateral flapping balances tail rotor thrust (e.g., no lateral cyclic movement by pilot)

- Initial roll angle and ground slope = 0

- Initial roll rate = 2 degrees/second

- Lateral center-of-gravity offset = 0.2 inch to the right

With no corrective control inputs, a point of inevitable rollover occurs at t = 2.33 seconds due to small destabilizing roll moment from main rotor thrust. For this configuration, the static rollover angle is 37 degrees and the critical rollover angle is 17 degrees.

4.3.3.1 Initial Roll Rate

The effect of initial roll rate on dynamic rollover is shown in Figure 13. The rollover point time is defined as the time required for the helicopter to reach the static rollover angle, as shown in Figure 12. There are no corrective pilot inputs introduced for these cases. If the initial roll rate increases, the time until the aircraft reaches the static rollover angle is decreased, thus requiring faster pilot reaction time to prevent rollover. This means that it is important for the pilot to minimize roll rates, since small increases in roll rate have a large influence on the time available for the pilot to take corrective action. The initial roll rate has two main effects.

- It increases the angular momentum of the aircraft that requires more control power to overcome.

- The stabilizing moment from the weight vector is rapidly reduced, which causes further increases in angular momentum.

4.3.3.2 Ground Slope

The effect of ground slope angle on dynamic rollover is presented in Figure 14. As the slope angle is increased in the roll direction, the rollover point time is reduced by the following factors:

- The stabilizing moment from the helicopter weight, as shown in Figure 12, is reduced.

- The amount of roll required to reach the static rollover angle is reduced by the slope angle.

This reduction in rollover time requires more pilot attentiveness and faster reaction time to prevent dynamic rollover.

4.3.3.3 Tail Rotor Thrust

The tail rotor thrust can create a destabilizing roll moment for the helicopter rolling about a skid, as shown in Figure 12. Using the baseline configuration, corrective pedal inputs were

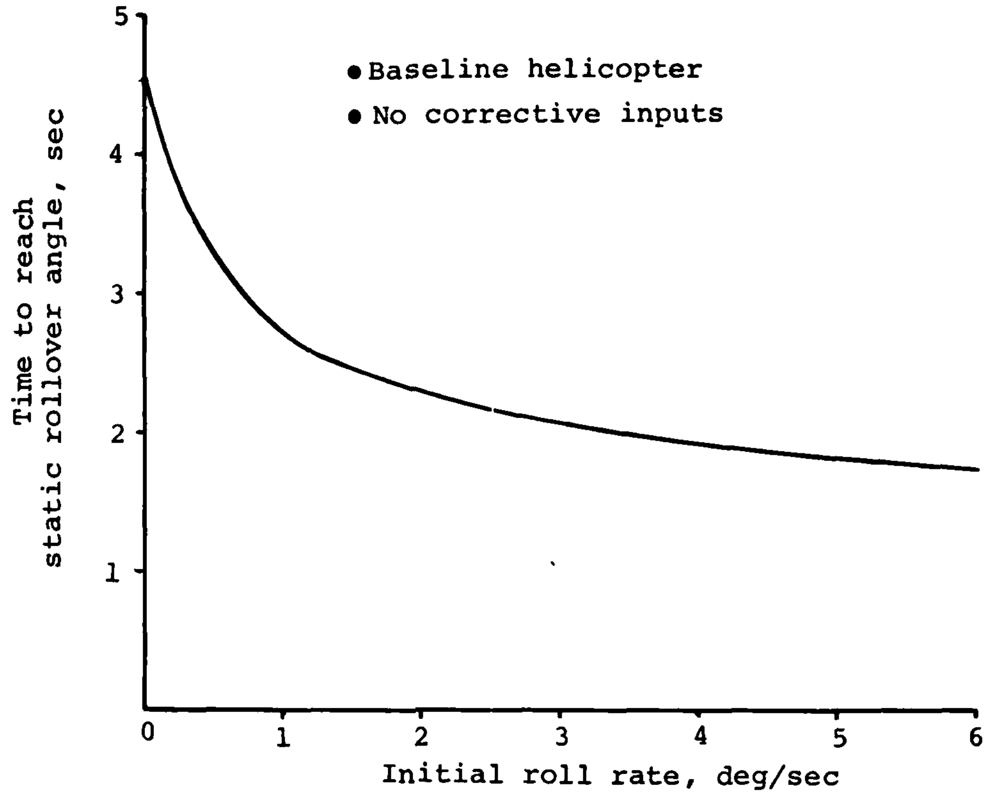


Figure 13. Effect of initial roll rate.

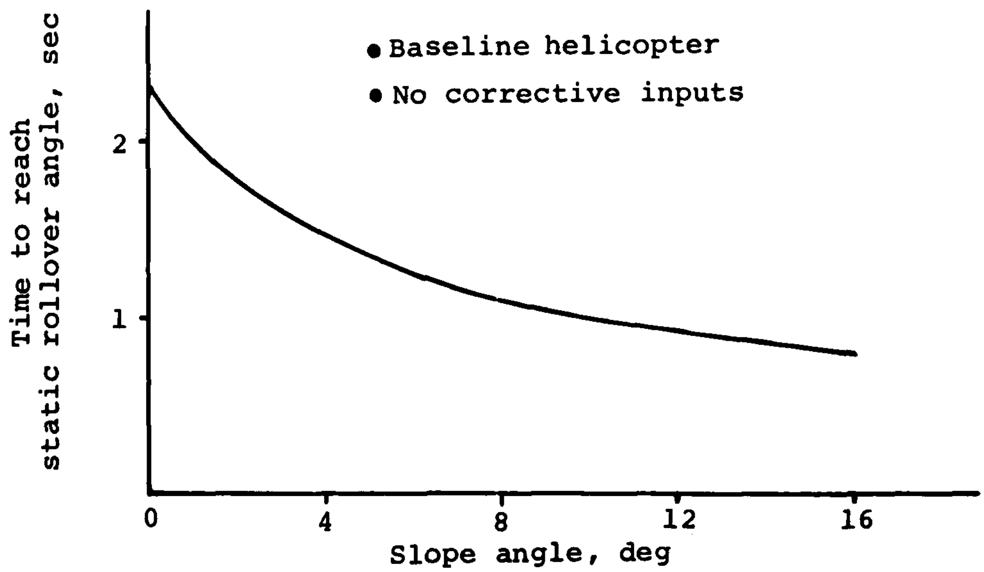


Figure 14. Effect of slope angle.

applied to determine the effect on rollover. The pedal control (i.e., tail rotor thrust) was varied linearly from trim position to full right pedal in 2 seconds. Using a pilot delay time of 0.5 second, dynamic rollover could not be prevented by tail rotor thrust application for the baseline case. Since 0.5 second is a short pilot reaction time, the tail rotor thrust was not considered to be a useful means of preventing rollover. Since right pedal inputs can contribute a stabilizing roll moment, tail rotor thrust management may make it easier to arrest the rollover when used in conjunction with other means. However, aircraft yaw trim may be upset by applying right pedal.

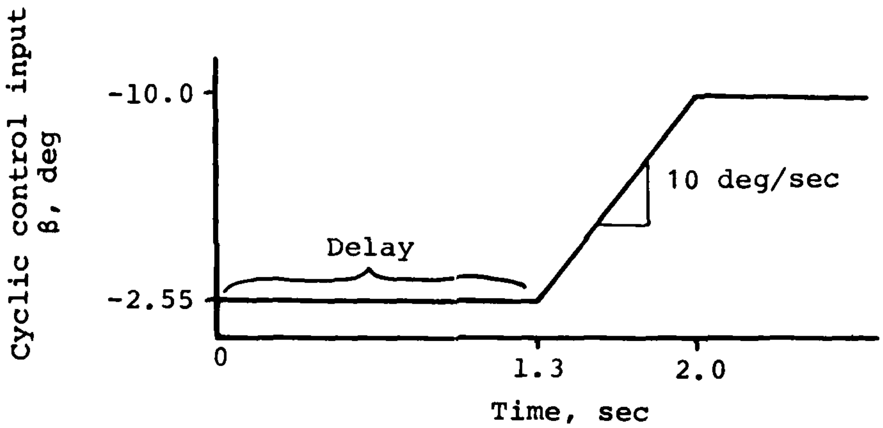
4.3.3.4 Main Rotor Cyclic

The main rotor cyclic control that is used to control aircraft roll in flight is much less effective in controlling rollover when the aircraft is in ground contact. The reasons for the difference in cyclic effectiveness are as follows:

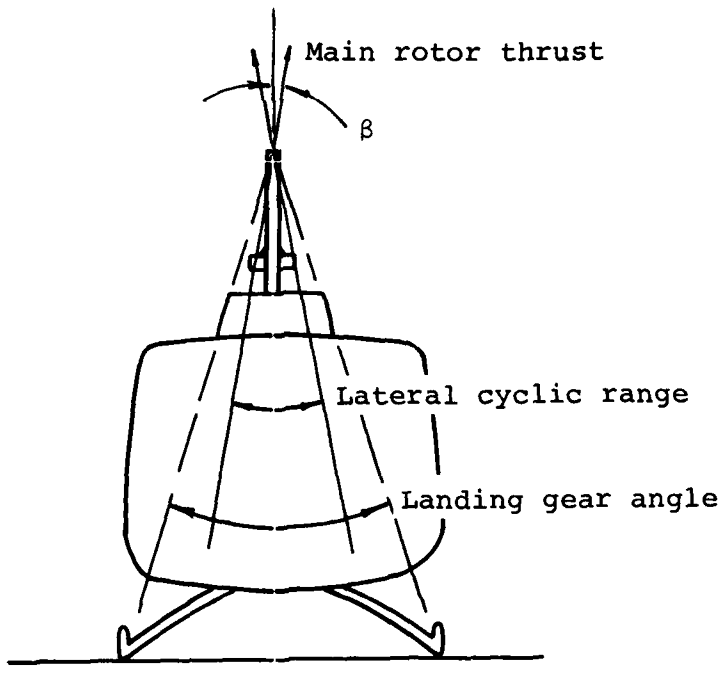
- The cyclic range is generally less than the gear footprint angle, as shown in Figure 15(b). For this reason, the cyclic control cannot produce a stabilizing rolling moment, but can be used to reduce the destabilizing effect of the rotor thrust.

- When rolling about a skid, the moment of inertia is typically greater than four times the inertia about the center of gravity. Thus, control inputs that produced rapid aircraft response in flight will provide sluggish response when in ground contact.

A simulation using the baseline helicopter was done to study the effect of cyclic control on dynamic rollover. Referring to Figure 12, angle β was varied as a function of time to simulate the response of the rotor disc due to a cyclic input. Since the control response lag, rotor damping, and control system kinematics are not modeled in the analysis, angle β can be interpreted as the cyclic pitch input. A cyclic input rate of 10 degrees/second was used to simulate the pilot's corrective input, as illustrated in Figure 15(a). In order to arrest the 2 degrees/second initial roll rate and prevent dynamic rollover, the cyclic input delay time could not exceed 1.30 seconds. If the cyclic input was delayed longer than 1.30 seconds, the aircraft would roll over due to excessive angular momentum. Thus, corrective cyclic control can be used to prevent rollover in some rollover conditions. However, due to its limited effectiveness, the cyclic control should be used in conjunction with other control means.



(a) Cyclic input profile.



(b) Comparison of lateral cyclic limits and gear footprint angle.

Figure 15. Lateral cyclic limitations.

4.3.3.5 Main Rotor Collective

Although main rotor collective is not used to control aircraft roll attitude in flight, main rotor thrust reduction through collective inputs is a very effective way to prevent dynamic rollover. If the main rotor thrust is reduced, the stabilizing rolling moment from the helicopter weight can prevent rollover. The effect of collective, or rotor thrust, was investigated using the baseline configuration. The collective was reduced at a rate of full-up to full-down in 2 seconds, as recommended by Reference 4. Very fast collective reduction could produce blade strikes or fuselage bounce. To prevent dynamic rollover for the 2 degrees/second initial roll rate, a delay up to 1.3 seconds in the collective input could be tolerated and still recover from an impending rollover. A collective input delay greater than 1.3 seconds would result in dynamic rollover. Of all the aircraft controls available, collective is the single most effective means to prevent dynamic rollover once the pilot responds to the situation.

4.3.4 Dynamic Rollover Improvements

From the foregoing analysis, it was apparent that several factors are needed to prevent dynamic rollover.

- Improved pilot awareness of impending rollover. Due to the limited time available for correction, a warning device and possibly an automatic sensing and correction system is needed. The flight control responses are different when the aircraft is nearly airborne but still in some ground contact as compared with in-flight response. Thus, improved pilot training and adherence to the published flight procedures are needed.

- Wider landing gear stance. Obviously, as the main landing gear is moved further outboard, the pivot point will also move further from the aircraft cg, thus reducing the potential of rollover. The landing gear could be permanently mounted, or quickly deployable outriggers could accomplish the same effect.

These potential improvements are discussed in detail in Section 5.1.

4.4 CRASH IMPACT ANALYSIS

4.4.1 Approach

To study lateral rollover impact of helicopter structures, analysis of the following areas is involved:

- Landing gear

- Lateral fuselage impact

- Roof impact

- Blade strike and associated pylon loads

- Pylon rollover loads

During rollover, it is important that the structure provides a protective shell around the occupied area. It is preferable to prevent rollover from occurring, but in the event that it does occur, the fuselage should be capable of withstanding side and roof impact loads. In addition, the main rotor pylon and support structure should be capable of withstanding blade strike and rollover loads. For design of future helicopter crashworthy structures that would provide improved protection for lateral rollover impacts, comprehensive analytical tools are needed that are capable of predicting the complex structural behavior for this type of condition.

For this investigation, the Lockheed KRASH structure crash simulation (described in References 12 and 13) was used for analysis of the airframe rollover response. The NASTRAN structure analysis program, described in Reference 14, was used for analysis of pylon loads due to blade strike. A typical KRASH structure model of the UH-1 helicopter is shown in Figure 16. The KRASH model represents the structure crash impact response with nonlinear beam and spring elements with load-deflection properties derived from tests or analyses.

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[12]Whittlin, G., and Gamon, M. A., EXPERIMENTAL PROGRAM FOR THE DEVELOPMENT OF IMPROVED HELICOPTER STRUCTURAL CRASHWORTHINESS ANALYTIC AND DESIGN TECHNIQUES, Lockheed-California Company; Technical Reports 72-72A and 72-72B, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1973, AD 764985, AD 764986.

[13]Whittlin, G., and Park, K. C., DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF PROCEDURES TO DETERMINE NONLINEAR LOAD-DEFLECTION CHARACTERISTICS OF HELICOPTER SUBSTRUCTURES SUBJECTED TO CRASH FORCES, Lockheed-California Company; Technical Reports 74-12A and 74-12B, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1974, AD 784191, AD 784192.

[14]THE NASTRAN USER'S MANUAL, NASA SP-222(03), National Aeronautics and Space Administration, Washington, D. C., July 1976.

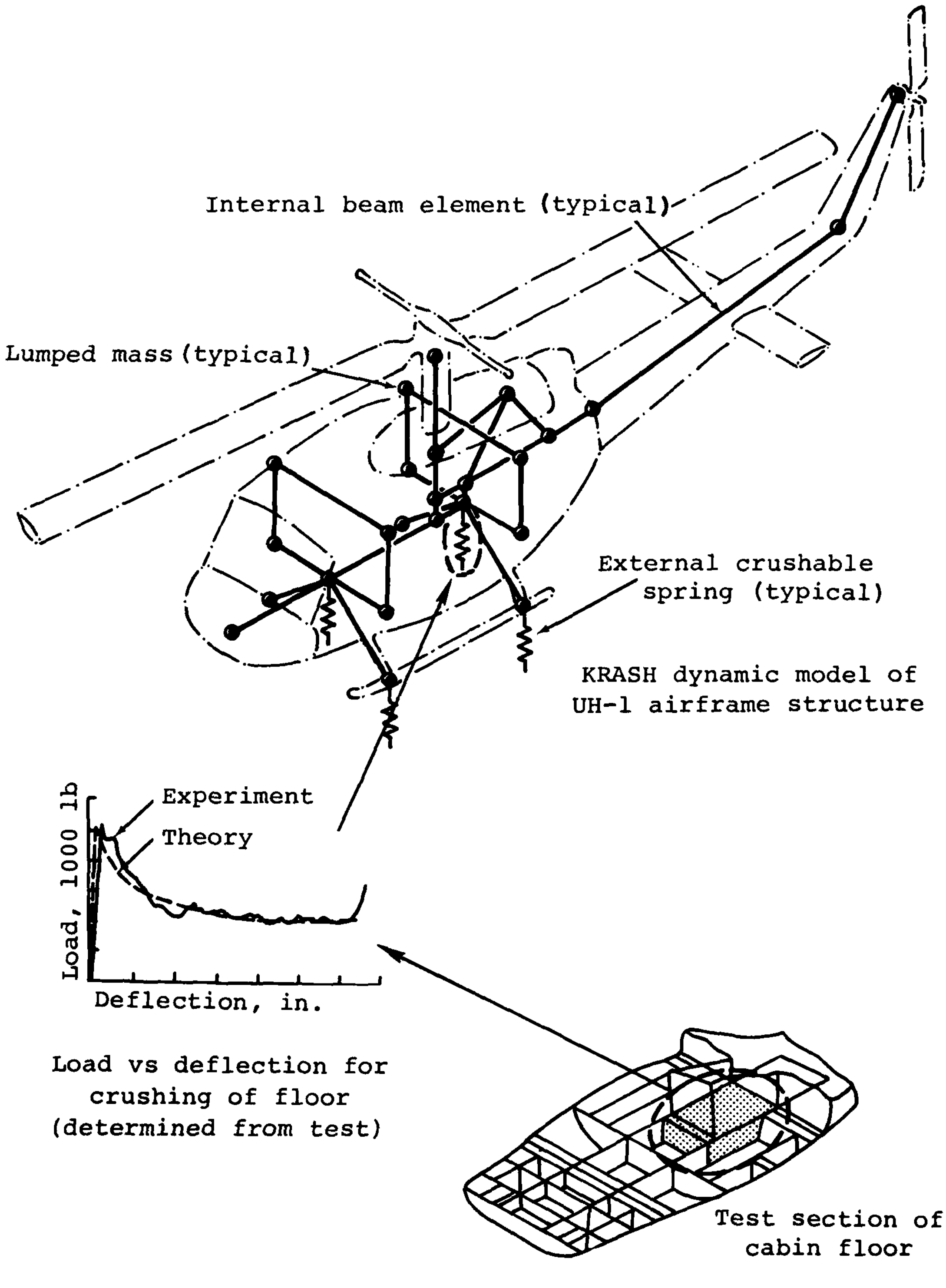


Figure 16. UH-1 airframe KRASH math model.

Areas assumed important to the structure response are represented in the KRASH model. A typical lateral rollover sequence is shown in Figure 17. The areas of the airframe structure that are important for this type of impact are the landing gear, fuselage rollover frame, and transmission support. Typical load-deflection properties for the fuselage rollover frame and transmission support are shown in Figure 18 and are characterized by abrupt loss of load-carrying capability.

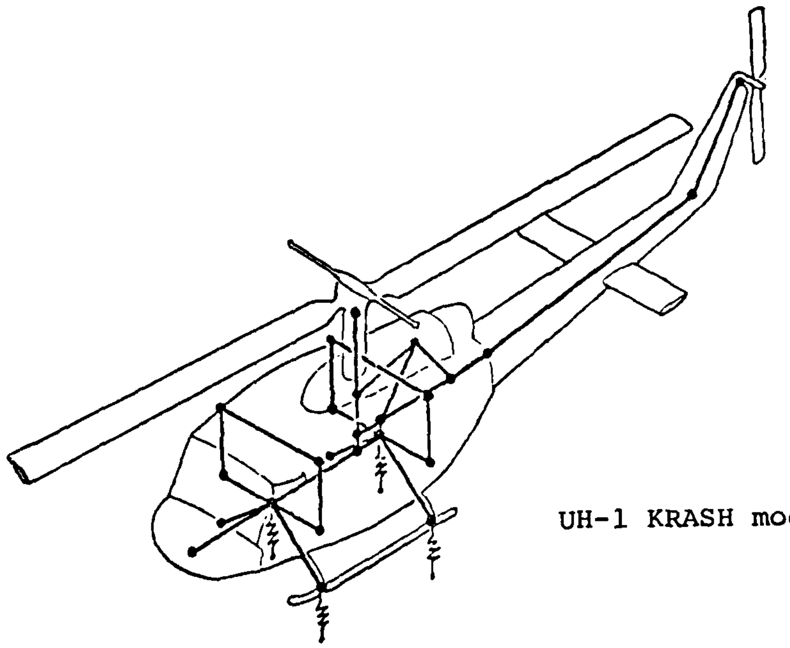
In order to evaluate the KRASH program for the analysis of the lateral rollover structure response of the helicopter, two types of models were used. A simple KRASH model was used to perform rollover parametric studies that involved several computer runs, thus permitting minimum run times. A more complete, three-dimensional UH-1 KRASH model, shown in Figure 16, was analyzed to evaluate the program for simulation of lateral rollover response of the entire airframe.

A NASTRAN analysis of a Model UH-1 blade was performed in order to evaluate the program capability for computing pylon loads due to blade strike.

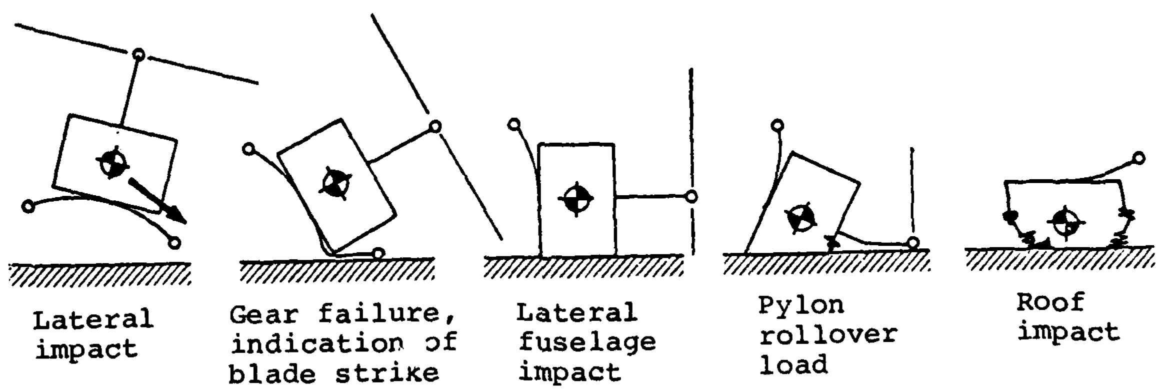
4.4.2 Simplified KRASH Model

A simple three-dimensional KRASH model was developed to investigate the roll attitude required at impact to initiate rollover. The model was also used to study the effect of the skid landing gear on prevention of rollover. The results from the simple model analysis guided the detailed UH-1 KRASH model study as to critical roll attitude and maximum simulation time for rollover. The crash impact rollover performance of the UH-1 helicopter was investigated with the simple three-dimensional KRASH analytical model shown in Figure 19.

The fuselage was idealized as a rigid body. A single mass point was located at the helicopter center of gravity to represent the weight/inertia properties of the Model UH-1. The weights, inertias, and static rollover angles are shown in Figure 20. Massless node points rigidly offset from the center-of-gravity mass point were used to define the geometry of the forward and aft bulkhead frames at fuselage stations 71.62 and 163.00, respectively. The crushing characteristics of the floor, sidewall, and roof were represented with lateral and vertical external crushing springs. The vertical spring parameters for the floor were obtained from the UH-1 model documented in Reference 12. For simplification purposes, the sidewall lateral and roof vertical spring parameters were assumed the same as the floor vertical. The standard skid landing gear idealization was taken from the UH-1 KRASH model

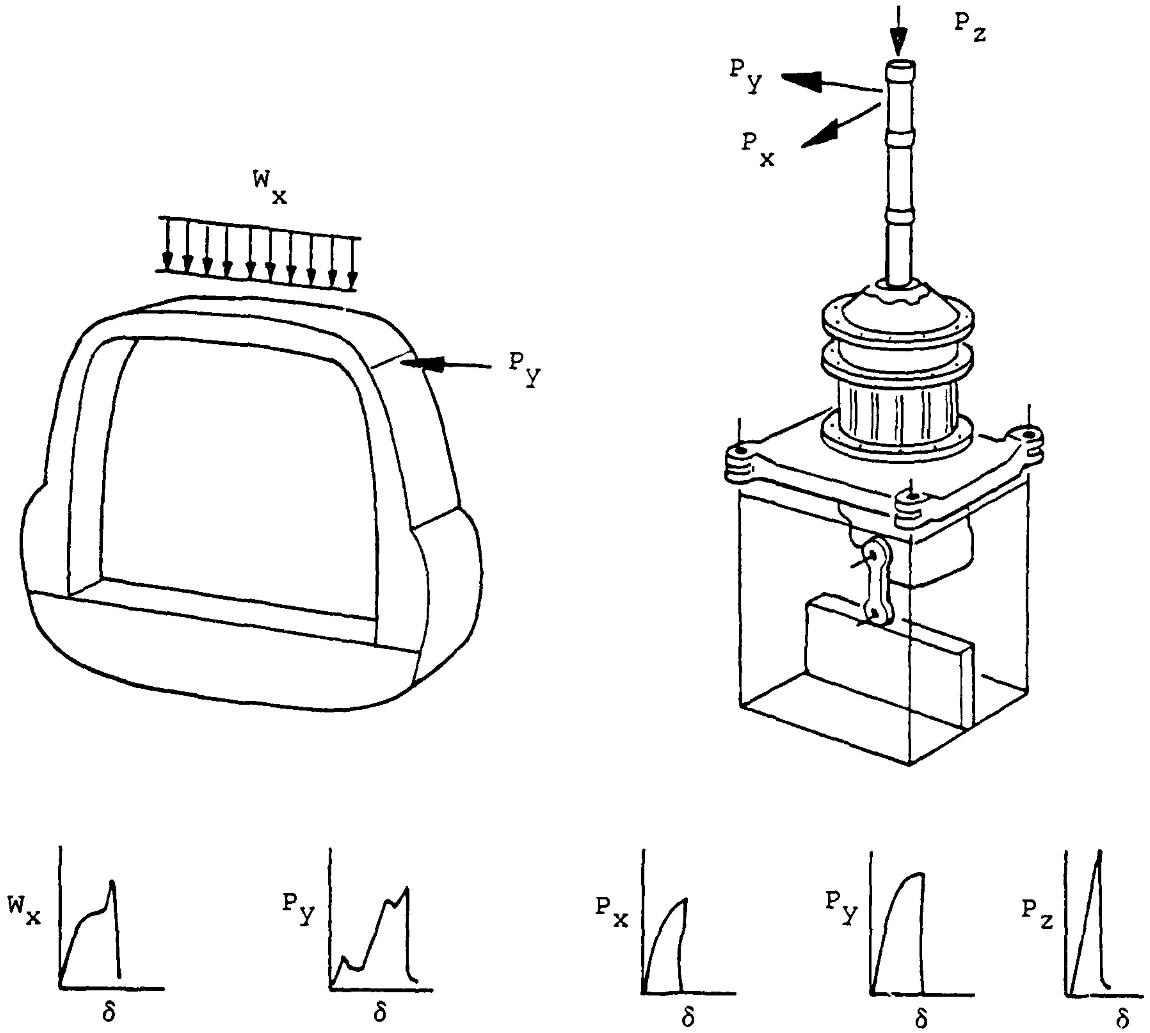


UH-1 KRASH model



Typical sequence of lateral impact with rollover

Figure 17. KRASH analysis of lateral impact rollover.



Forward rollover frame

Transmission support

Figure 18. Typical load deflection characteristics.

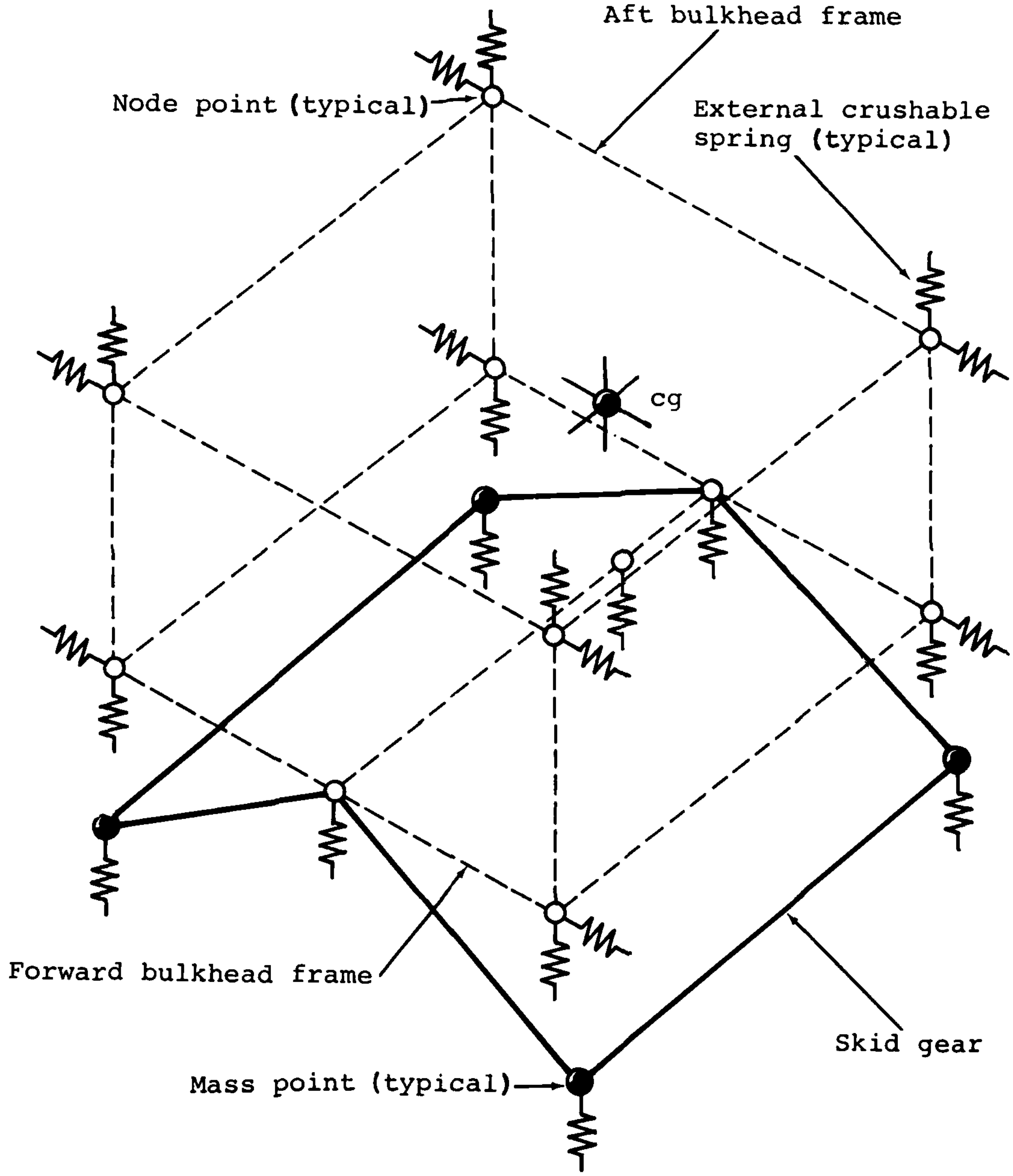


Figure 19. Simplified KRASH model.

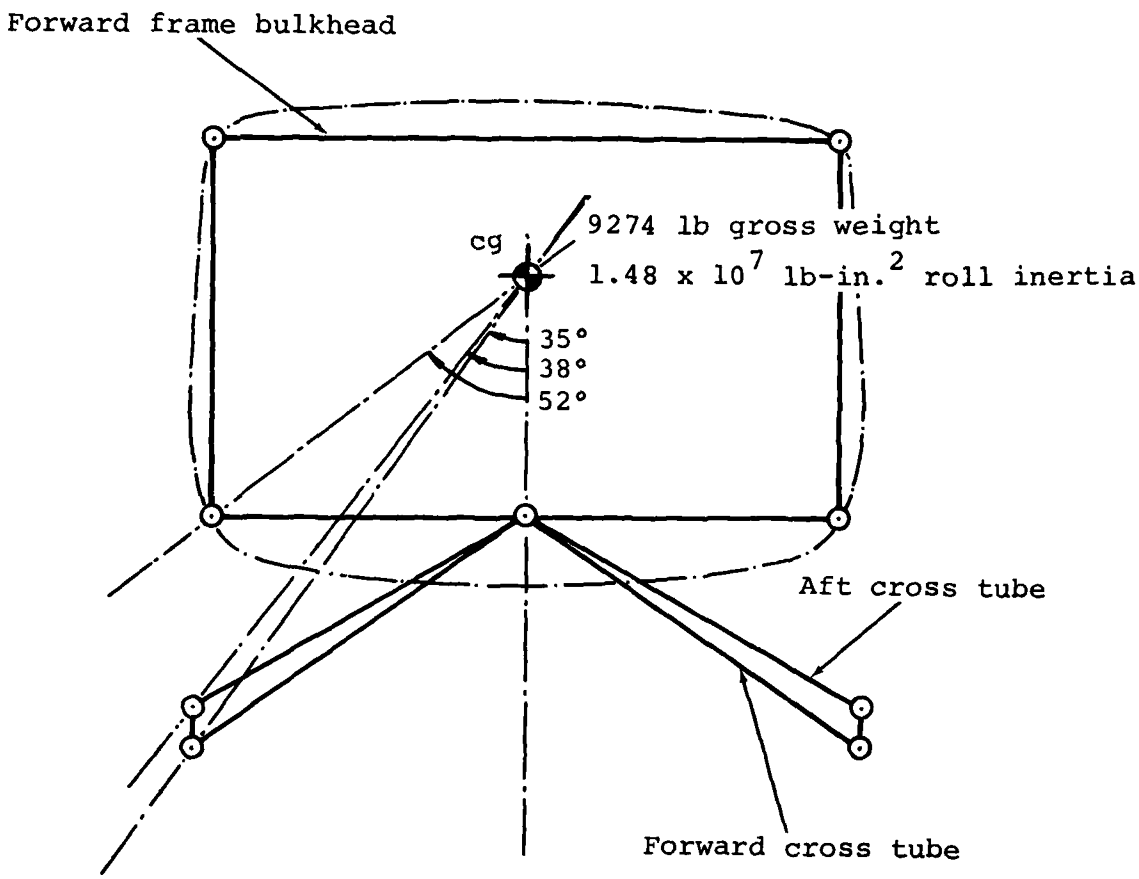


Figure 20. UH-1 KRASH model static rollover angles.

documented in Reference 15 and included mass point geometry and weight/inertia properties, beam element linear and non-linear stiffness parameters, and external crushing spring characteristics.

4.4.2.1 Simplified KRASH Model Analysis

The simple three-dimensional UH-1 KRASH model was studied with and without the standard skid landing gear to determine the gear's effect on the crash impact rollover characteristics of the UH-1 helicopter. The math model was analyzed for a 30 fps vertical impact velocity onto a rigid zero-sloped surface. The initial cg roll attitude was varied as shown in Table 7. Note that the cases analyzed assumed an intial cg roll rate of zero degrees per second. Dynamic loadings from blade strikes were not included (e.g., rotor assumed not to be turning).

TABLE 7. SIMPLE MODEL UH-1 KRASH ANALYSIS CASES WITH AND WITHOUT SKID LANDING GEAR

Case	Vertical Velocity (fps)	Initial Roll Attitude (deg)
1	30	30
2	30	40
3	30	50
4	30	60

The maximum simulation time used in the KRASH analysis for each of the cases was 1500 milliseconds. The fixed time step selected for the predictor-corrector integration method in KRASH was 20 microseconds. These values were chosen after a preliminary trial-and-error KRASH analysis of Case 3 with skid gear was made in which the time step and simulation time were varied. The checkpoint-restart feature in KRASH was used for all cases such that the maximum simulation time was achieved in steps of 500 milliseconds, thereby keeping the computer time

[15] Cronkhite, J. D., et al., INVESTIGATION OF THE CRASH IMPACT CHARACTERISTICS OF ADVANCED AIRFRAME STRUCTURES, Bell Helicopter Textron; Technical Report 79-11, Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, September 1979.

per run at a reasonable value. In order to reduce "turnaround" time for these multirestart cases, a procedure was developed that provided the user with capability to submit KRASH jobs via remote terminal and used temporary disk storage rather than magnetic tape for the checkpoint-restart files.

As an example of the data available from the simplified KRASH analysis, the important events during the crash impact and time of occurrence for each is shown below in Table 8 for Case 1 conditions with skid gear intact.

TABLE 8. TIME HISTORY OF SIMPLIFIED KRASH MODEL EVENTS

	Simulation time (MSEC)	
Impact Event Description	Start	End
Forward right skid vertical impact	0	25
Aft right skid vertical impact	10	50
Aft right floor vertical impact	45	165
Forward right floor vertical impact	50	145
Aft right floor lateral impact	65	135
Forward right floor lateral impact	65	125
Aft right skid vertical impact	265	320
Aft left skid vertical impact	270	285
Forward left skid vertical impact	340	360
Aft right skid vertical impact	435	460
Forward left skid vertical impact	850	860
Aft right skid vertical impact	875	885*

* Note: Analytical solution goes unstable

4.4.2.2 Simplified KRASH Model Results

For the simple UH-1 model with and without skid landing gear, the KRASH analytical results presented in Figures 21 and 22 include time histories of the cg roll angle and roll velocity, respectively. In general, the following conclusions can be deduced from the simplified KRASH analytical simulations.

- The skid landing gear is beneficial in the prevention of rollover. As the cross tubes deflect and spread upon impact, an "outrigger" effect becomes apparent. In Figure 21, the cg roll angle time history shows that

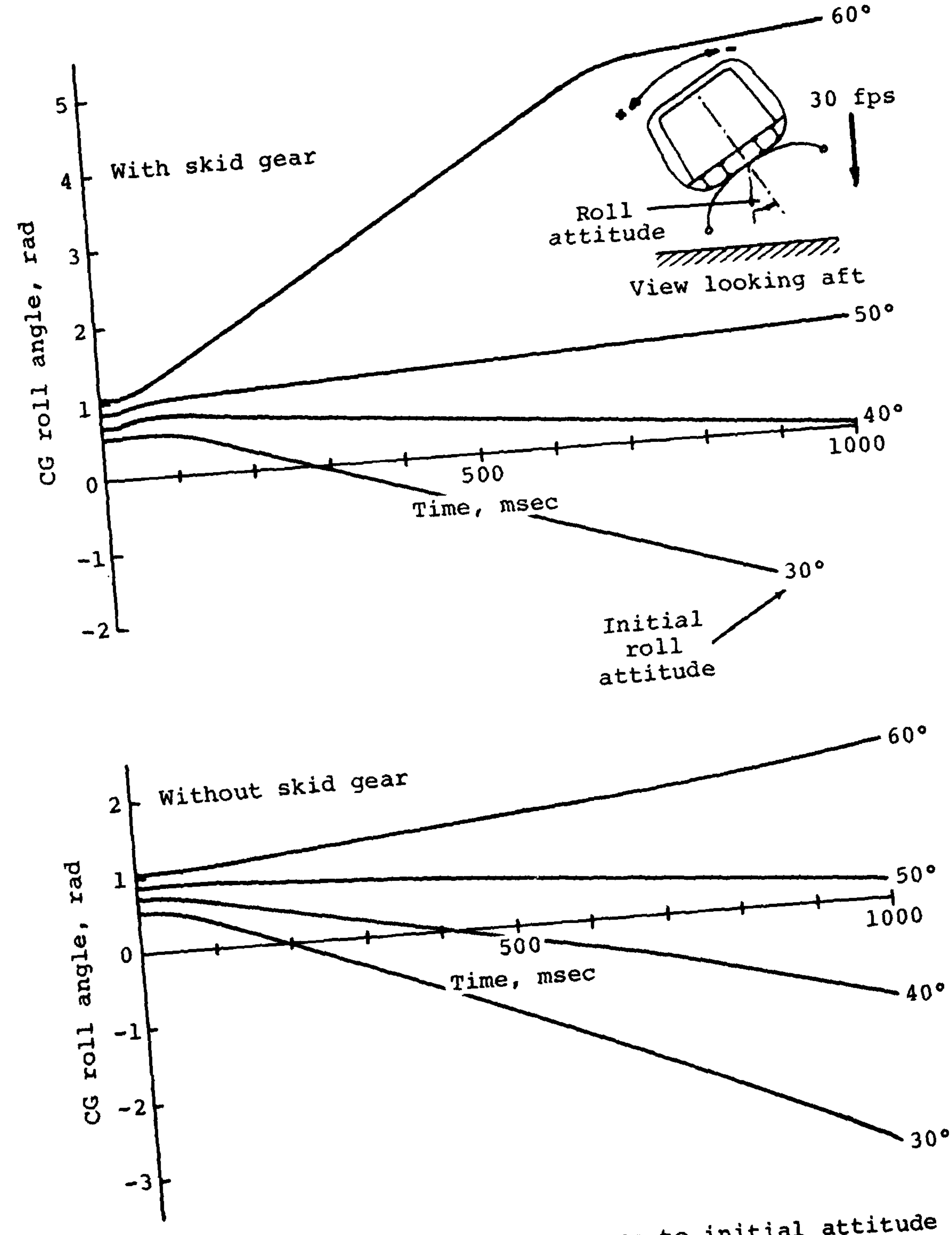


Figure 21. CG roll angle response to initial attitude and landing gear.

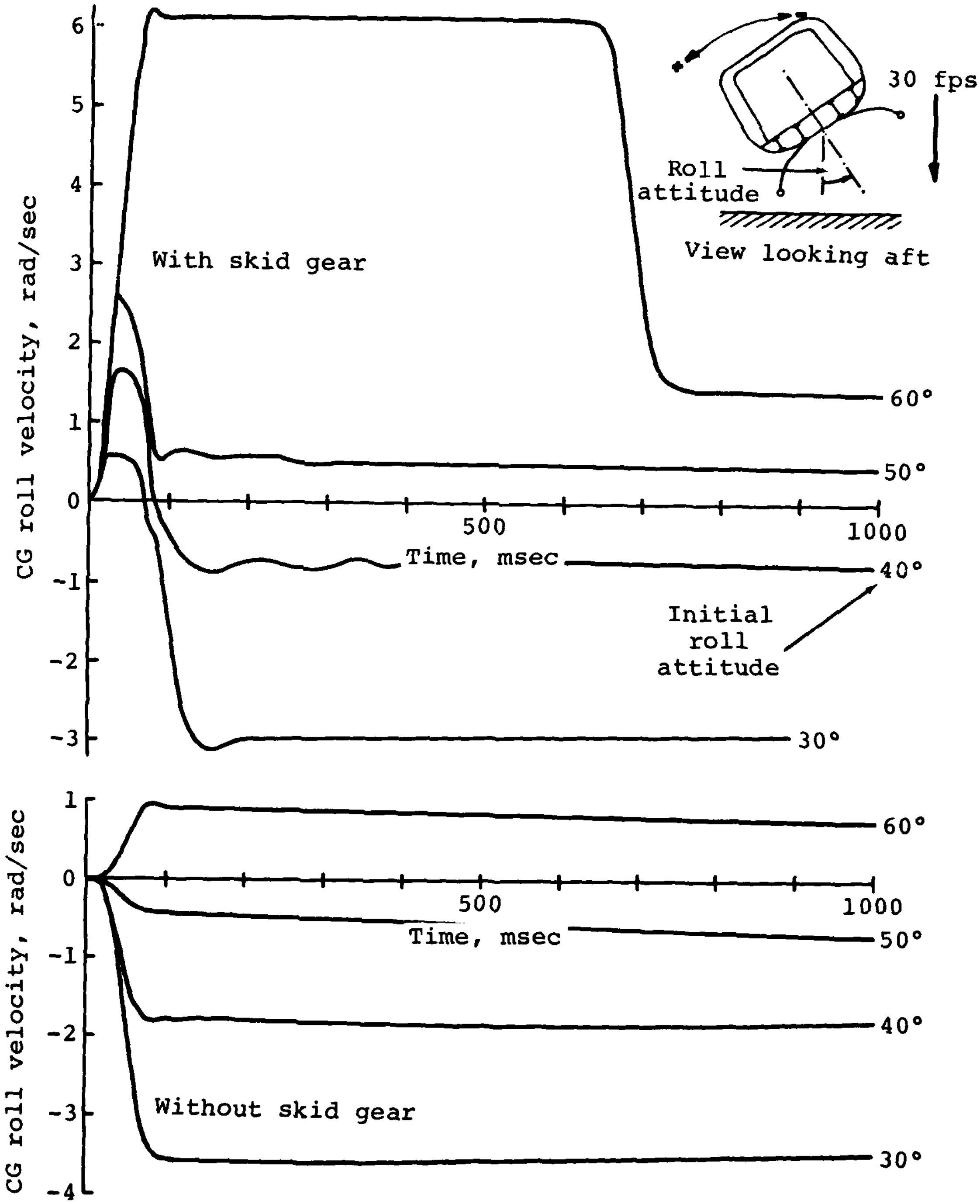


Figure 22. CG roll velocity response to initial attitude and landing gear.

the aircraft with skid gear and initial roll attitudes of 30 and 40 degrees do not roll over (indicated by a negative slope). Without skid gear, aircraft roll attitudes up to 50 degrees will result in the aircraft rolling back upright rather than rolling over. The chart further substantiates the comments on the advantages of a rectangular-shaped fuselage over a circular-shaped fuselage discussed in Section 3.1. By interpolating between 40- and 50-degree curves, an aircraft roll angle attitude that would be critical for rollover is determined to be approximately 10 degrees greater than the static rollover angle shown in Figure 20. This improvement in rollover resistance is due to the skid gear extending outboard as outriggers as they deform.

- For aircraft rollover, a greater initial roll angle attitude is required for the Model UH-1 without the skid landing gear than with the gear. This observation is seen clearly in Figures 21 and 22 by comparing the 50-degree curves. The Model UH-1 without gear exhibits no rollover tendancies (i.e., no positive cg roll angle slope and no residual positive cg roll velocity), whereas the Model UH-1 with gear does. The improvement is due solely to the increased static rollover angle for the Model UH-1 without landing gear. The KRASH results show that rollover begins to occur when the initial roll angle attitude of the Model UH-1 without landing gear equals the static rollover angle.

- The computer run times using a time step of 20 microseconds were typically 1.8 CPU seconds per simulation millisecond for the model with a skid gear and 1.5 without a skid gear.

- The UH-1 math model without a skid gear yielded a much more stable analytical solution for KRASH simulation than the same model with a skid gear. This is apparently due to the relatively soft skid landing gear structure, which deforms a great amount upon impact. As a result, large fluctuations of mass point energy deviation occur for those mass points associated with the skid gear when the gear fails and the masses are allowed to displace to infinity.

- Although the simulation time used in the KRASH analysis of the simple three-dimensional UH-1 model was 1500 milliseconds to allow rollover to occur, the response time histories indicate that a total simulation time of 160 milliseconds is adequate to investigate the initial impact events. Once the math model comes off of ground contact, the response time histories involve primarily long duration rigid body motions. Large time steps can be used during this portion of the simulation to reduce run times.

4.4.3 Detailed UH-1 Airframe KRASH Model

A KRASH model of the UH-1 airframe was used to study the helicopter structure response during rollover and the protective shell integrity around the occupied cabin area during the rollover sequence. Also, the main rotor pylon loads during rollover, other than those from a blade strike, were determined. The information gained from the Model UH-1 analysis could be used to evaluate KRASH for simulation of lateral rollover response, as well as investigate the fuselage sidewall and roof structure and pylon retention capability to withstand rollover loads.

This KRASH analytical model is shown in Figure 16 and is documented extensively in Reference 15. For the purpose of the rollover study, the UH-1 model was modified by the addition of sidewall lateral and roof vertical external crushing springs at the forward and aft bulkhead frames located at fuselage stations 71.62 and 163.00, respectively. As discussed earlier for the simple UH-1 model, the parameters for the additional crushing springs were assumed to be the same as the floor vertical springs.

4.4.3.1 Impact Conditions

Even for the simplified KRASH model, it was apparent that long simulation times were required for a complete crash impact rollover analysis. Consequently, the computer run costs involved to perform extensive parametric analyses for the built-up UH-1 model were prohibitive; however, one case was run to demonstrate that rollover conditions can be analyzed with KRASH. To ensure rollover would occur, an initial roll angle attitude of 60 degrees was used. The other initial conditions were 30 fps vertical impact velocity and a rigid, zero-sloped impact surface. The maximum simulation time was 750 milliseconds and the integration time step was 20 microseconds. The checkpoint-restart feature in KRASH was employed to run 150 milliseconds of simulation time per computer job until the full analysis was completed.

4.4.3.2 Results

Since the built-up three-dimensional UH-1 KRASH model could not be extensively analyzed for crash impact rollover due to computer cost limitations, the results for the one case examined are presented briefly.

Figure 23 shows the forward frame bulkhead, forward cross tubes, and main rotor pylon deflections at various time points in the simulation. The rollover sequence reveals large structural deformations of the skid gear and pylon. As these elements fail or rupture, they are removed (as shown in Figure 23). Forward frame deformation indicates that the protective shell around the occupied cabin area is preserved. However, the results can be misleading in that the modeling is not detailed enough to allow sidewall and roof buckling. As with the simple UH-1 model, the analysis exhibits much helicopter rebound that might not be realistic.

4.4.4 Simple vs Detailed KRASH Model Comparison

Table 9 shows a comparison of important crash impact events and time of occurrence of a 60-degree roll attitude at 30 feet/second vertical impact for simple and detailed UH-1 KRASH models.

TABLE 9. SIMPLE VS DETAILED KRASH MODEL COMPARISON

Impact Event Description	Simulation Time (MSEC)			
	Simple		Detail	
	Start	Stop	Start	Stop
Forward right skid vertical impact	0	5	0	22
Aft right skid vertical impact	5	85	6	84
Aft right floor lateral impact	15	95	14	84
Forward right floor lateral impact	15	100	16	140
Forward right floor vertical impact	-	-	40	82
Forward left roof lateral impact	605	695	-	-
Forward right roof lateral impact	-	-	742	750

Both the simple and detailed UH-1 models agree well for the initial impact events. However, as the simulation continues, structure deformation becomes more predominant in the detailed model, and the two models give somewhat different results. The crash impact rollover study of the Model UH-1 using KRASH showed the simple model to be good for parameter studies. Also, the simple model provided insight as to how long a simulation time is required for rollover to occur. The detailed model was more suited to studying a specific initial condition of interest where accurate representation of structure deformation is desired.

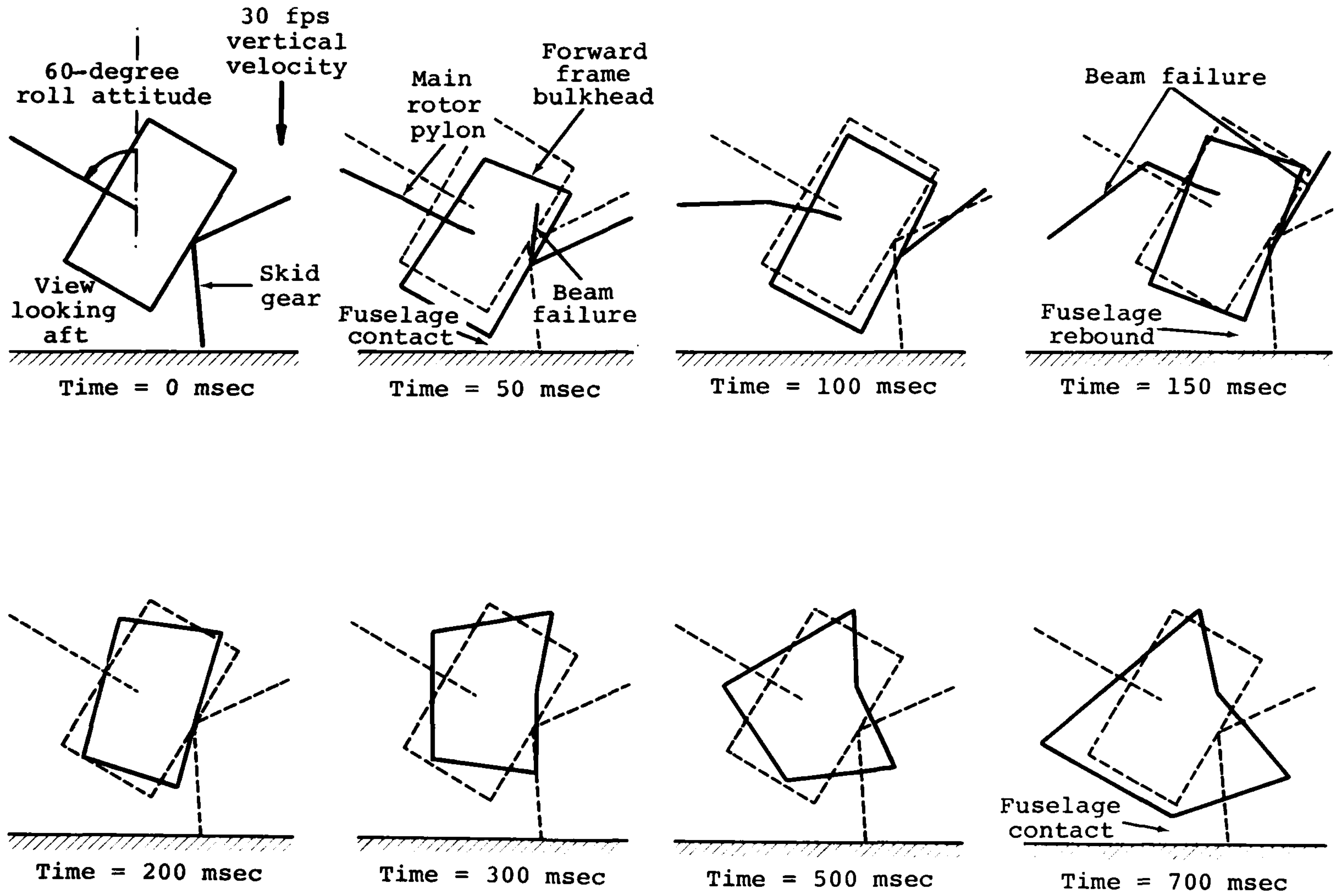


Figure 23. Detailed UH-1 KRASH model rollover sequence.

The computer cost for analyzing the detailed UH-1 KRASH model was fairly expensive. The ratio of CPU time to simulation time was 6.6 seconds per millisecond, or 77 CPU minutes for the total 700 millisecond simulation time on BHT's IBM 370/168 digital computer. Thus, the detailed model was roughly four times as expensive to run as the simple model.

4.4.5 Main Rotor Blade Strike

The NASTRAN analysis uses an elastic line representation of the rotor and included only in-plane blade response without the effects of rotating beam dynamics, beam/chord/torsion coupling, material and geometric nonlinearities and out-of-plane response that are important for ground strike. A simple elastic line NASTRAN model of the UH-1 main rotor blade was developed to investigate pylon loads resulting from blade strike. The analysis is intended to represent only an in-plane blade strike of an obstacle. Results can provide guidance in the improvement of pylon retention structure. The NASTRAN rotor/pylon analytical model is shown in Figure 24.

Analysis of severe in-plane blade strikes, when the blade tip is stopped by contact with a rigid obstacle or soil, can be conducted by assuming one blade tip is slowed down or stopped over a certain distance. The analysis proceeds until there is a failure in the blade. Then the simulation is stopped, the failed element is given a reduced stiffness to form a plastic hinge, and the analysis proceeds using the initial conditions from the point at which the blade failure occurred. The simulation proceeds until the peak pylon hub load reaction is determined. Using the pylon load-deformation data, an assessment can be made of whether pylon failure has occurred.

For a tree strike analysis, a load or impulse is applied to the blade tip representing the reaction to cutting a tree or shearing off the blade tip. As an example, the time history response of the pylon reaction load to a rotor strike, assuming a 3.6-pound-second impulse applied to the tip, would result in about 400 pounds of chordwise shear force at the main rotor hubs, as shown in Figure 25.

A complete analysis of rotor strike impact involves contact stress, three-dimensional stress wave propagation, transient structural response, and rotating beam dynamic theories. The NASTRAN analysis described above concentrates on the analysis of transient in-plane structural response of the rotor and pylon. The accident analysis results discussed in Section 2.2 show that many severe rotor strikes involved ground contact that resulted in hub/mast failure due to severe flapping. Analysis for this type of response will require consideration of rotating beam dynamics with out-of-plane response due to rotor contact with the ground during the rollover sequences.

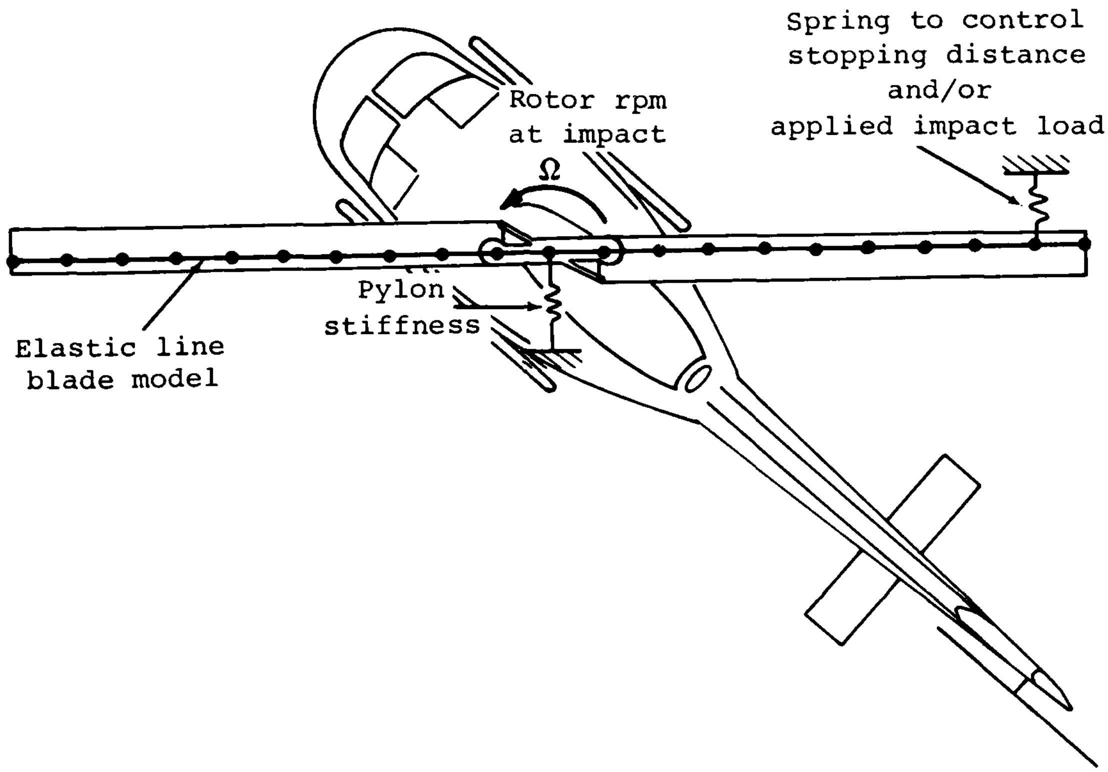


Figure 24. NASTRAN blade strike model.

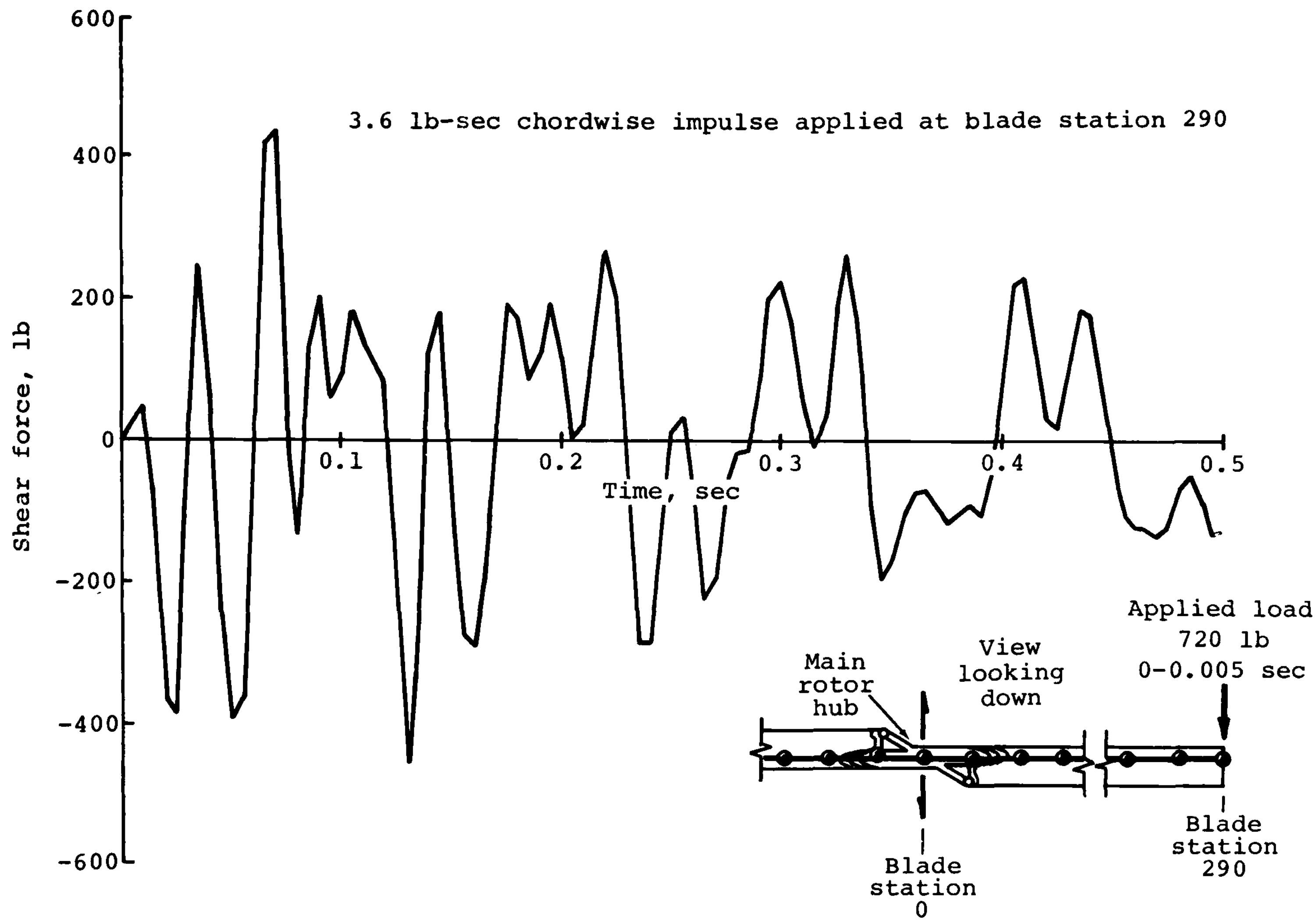


Figure 25. Model UH-1 hub chordwise shear force from blade strike.

5. DESIGN CONCEPTS

Protection from lateral rollover requires two approaches. Prevention of a lateral rollover is obviously the first and primary approach. However, not all rollovers are preventable; therefore, protection of the aircraft occupants during a lateral rollover is the second approach. Potential design concepts for each of these approaches based on the results of the accident analysis are discussed below.

5.1 PREVENTION OF ROLLOVER

Before a rollover can be prevented, it must be sensed and diagnosed as a problem. Some pilots apparently have difficulty in identifying this potential problem and responding properly in the limited time available. It appears that an electronic system could be developed that could reduce the number of lateral rollover accidents. The electronic systems could

- Sense an impending rollover
- Provide warning to pilot
- Automatically provide the needed corrective control responses
- Deploy outriggers to increase lateral stability
- Cancel automatic control inputs when correction is complete

If the landing gear point of pivot during a rollover is moved outboard, the lateral stability of the aircraft is increased. A fixed landing gear can be designed further outboard to get a wider tread. Retracted landing gear (wheeled or skid) can also be designed to give a wide tread.

5.1.1 Electronic Dynamic Rollover Protection System (DRPS)

5.1.1.1 Concept of DRPS. An electronic Dynamic Rollover Protection System (DRPS) to assist the pilot during takeoff and landing is an attractive concept. The rollover detection logic may be based on sensing the differences when pivoting about the aircraft cg in flight versus pivoting about a landing gear as occurs during a dynamic rollover. This difference is shown in Figure 26. Accelerometers and/or rate gyros installed near the vertical line through the aircraft cg at points A through E can be used to sense a rollover, as

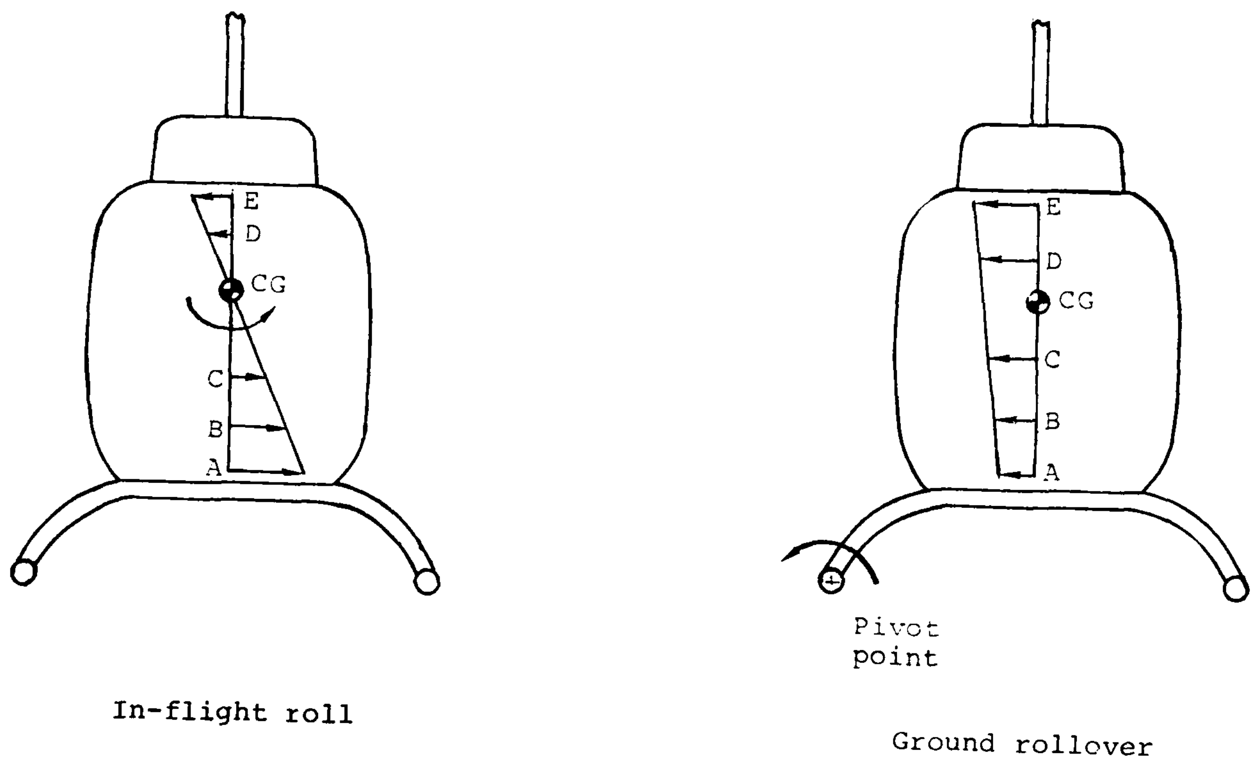


Figure 26. DRPS rollover sensing logic.

distinguished from an in-flight roll, and determine the roll rate. For example, an in-flight condition where the aircraft pivots about its cg would be indicated by the relative acceleration magnitude of point A greater than point B, and point B greater than point C. Furthermore, the direction of points A, B, and C would be opposite to points D and E. The DRPS would act only as a monitor during in-flight aircraft roll motion.

However, during a dynamic rollover, the pivot point is the outboard main landing gear. This would be indicated by the acceleration magnitudes of point A being less than point B, and point B being less than point C. Furthermore, the direction of acceleration would be the same for all points (A through E). After sensing a dynamic rollover, the DRPS would provide a warning light to the pilot and determine the appropriate means and amount of correction needed. The DRPS would then drive quick-acting actuators within the flight control system to make the required corrections. The DRPS would monitor the aircraft response to the corrective action and modify the corrective actions as necessary.

The DRPS could be activated by the pilot prior to takeoff, turned off during flight, and reactivated prior to landing. The DRPS would include a quick-acting actuator within the lateral cyclic, collective, and tail rotor controls.

Adding a gyro to determine aircraft motions not commanded by the pilot and additional circuitry can provide an automatic antitorque correction capability. Such a capability would greatly simplify the pilot workload and flight control coordination. Full-time automatic antitorque controls would permit standardization. For example, large displacements of left pedal are required at the termination of a hover landing or during a power recovery from an autorotation. Only a small left pedal displacement is needed to terminate a power-off autorotation. Thus, automatic antitorque control could make all three approach techniques the same, since no pedal movement would be required unless the pilot desired to change the aircraft heading. Such a system could eliminate many accidents presently caused by the pilot allowing a tail rotor strike to occur.

The concept of a DRPS using only the collective portion was evaluated for the baseline aircraft using the simulation technique described in Paragraph 4.3.3.5. The DRPS applies collective inputs (main rotor thrust reduction) proportional to roll rate when in ground contact. The results shown in Figure 27 indicate that time available for correction can be extended by increasing the collective gain (e.g., larger main rotor thrust reduction induces larger correcting moments). The collective gain, K, is defined as the magnitude of thrust change proportional to roll rate. An attitude sensor was not included in this parametric study but would be needed to sense a level attitude for DRPS reference. Once the aircraft is brought back from an impending rollover attitude to a level attitude, the DRPS control inputs would cease.

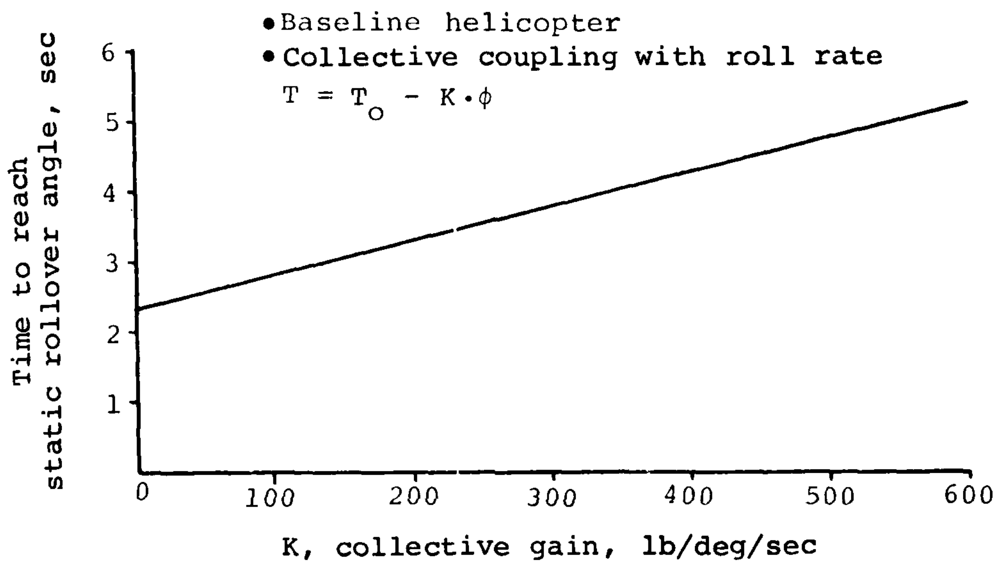


Figure 27. Effect of varying DRPS collective gain.

5.1.1.2 Mechanization Considerations. The concept of an electronic DRPS is contingent upon the quick response time of the system in sensing motions, accelerations, and rates; discriminating the signals so that a "potential rollover" decision can be made; and introducing proper control inputs to compensate for the potentially dangerous condition of dynamic rollover. As discussed above, fast-acting, large authority inputs are probably required. This safety consideration requires that the system be very reliable. For an electronic system, this typically requires redundancy and monitoring functions that detect any possible failures in the system.

The electronic DRPS could easily be implemented on a helicopter that utilizes fly-by-wire technology because of its inherent built-in redundancy and electronic computing capability. In addition, any type of cross-axis control input commands could be easily mechanized by electrical signal summations. As new helicopter models emerge, systems of this sort should certainly be considered.

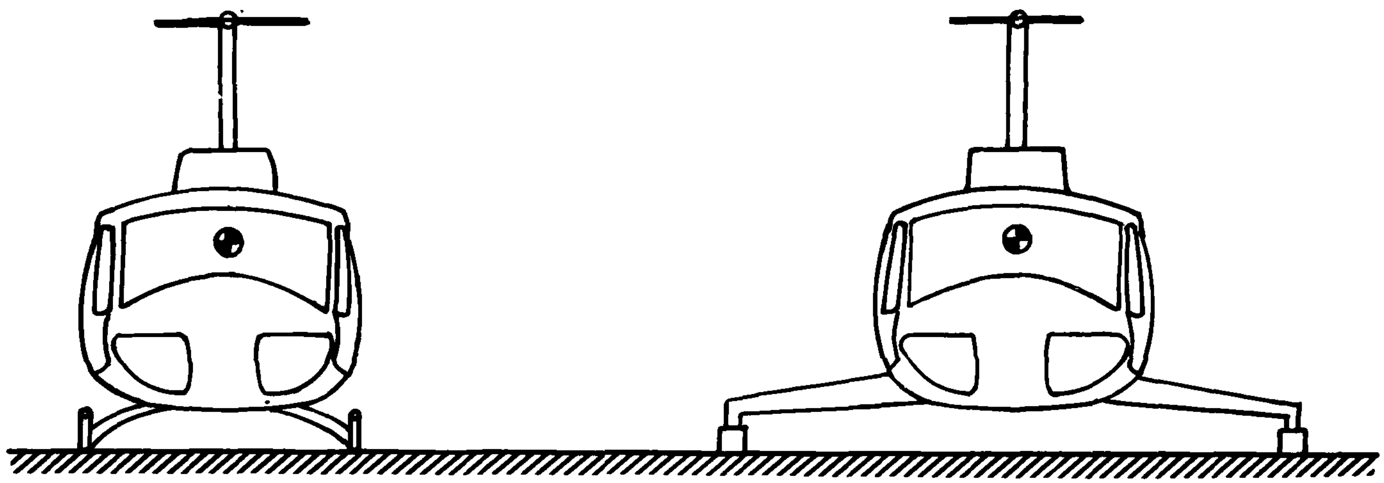
5.1.2 Lateral Structure

Another approach to preventing a lateral rollover is to move the structural point of pivot further outboard. This would effectively increase the critical rollover angle, static rollover angle, time available for correction, and the effectiveness of reducing main rotor thrust. Locating the pivot point further outboard can be achieved by wider tread landing gear, low wing, winged landing gear, and deployable outriggers.

5.1.2.1 Landing Gear. The most direct approach to resolving the rollover problem is to increase the inherent lateral stability of the aircraft by designing the main landing gear ground contact as far outboard as possible. An extremely wide tread landing gear can conflict with present aircraft transportability requirements. Further study is needed to reconcile these potential differences.

Moving the landing gear ground contact point 4 feet further outboard on the baseline helicopter was investigated. Figure 28 shows a front view of the baseline helicopter and the wide gear concept. For rollover prevention, the aircraft roll attitude must be corrected between the level attitude and the extreme roll attitude in which the main rotor blade strikes the ground. Assuming full lateral cyclic correction and resultant flapping, the baseline helicopter has the range shown in Figure 29(a). The range for the wide gear concept is shown in Figure 29(b). Note that the baseline aircraft cg has risen to be almost directly above the pivot point, whereas the wide gear concept aircraft cg is still over 2 feet away from the pivot point. Thus, the wide gear concept enhances the use of the aircraft weight (by reducing main rotor thrust) to bring the aircraft back to the level attitude.

The wide landing gear concept was evaluated using the simulation technique described in Section 4.3.2. The wide gear design was compared with the baseline design using the collective input (e.g., for main rotor thrust reduction) described in Paragraph 4.3.3.5. The time available for pilot correction was increased significantly for the wide gear concept, as shown in Figure 30. The effectiveness of the DRPS would be greatly enhanced by combining it with a wider gear stance.



(a) Baseline

(b) Wide gear

Figure 28. Wide landing gear concept.

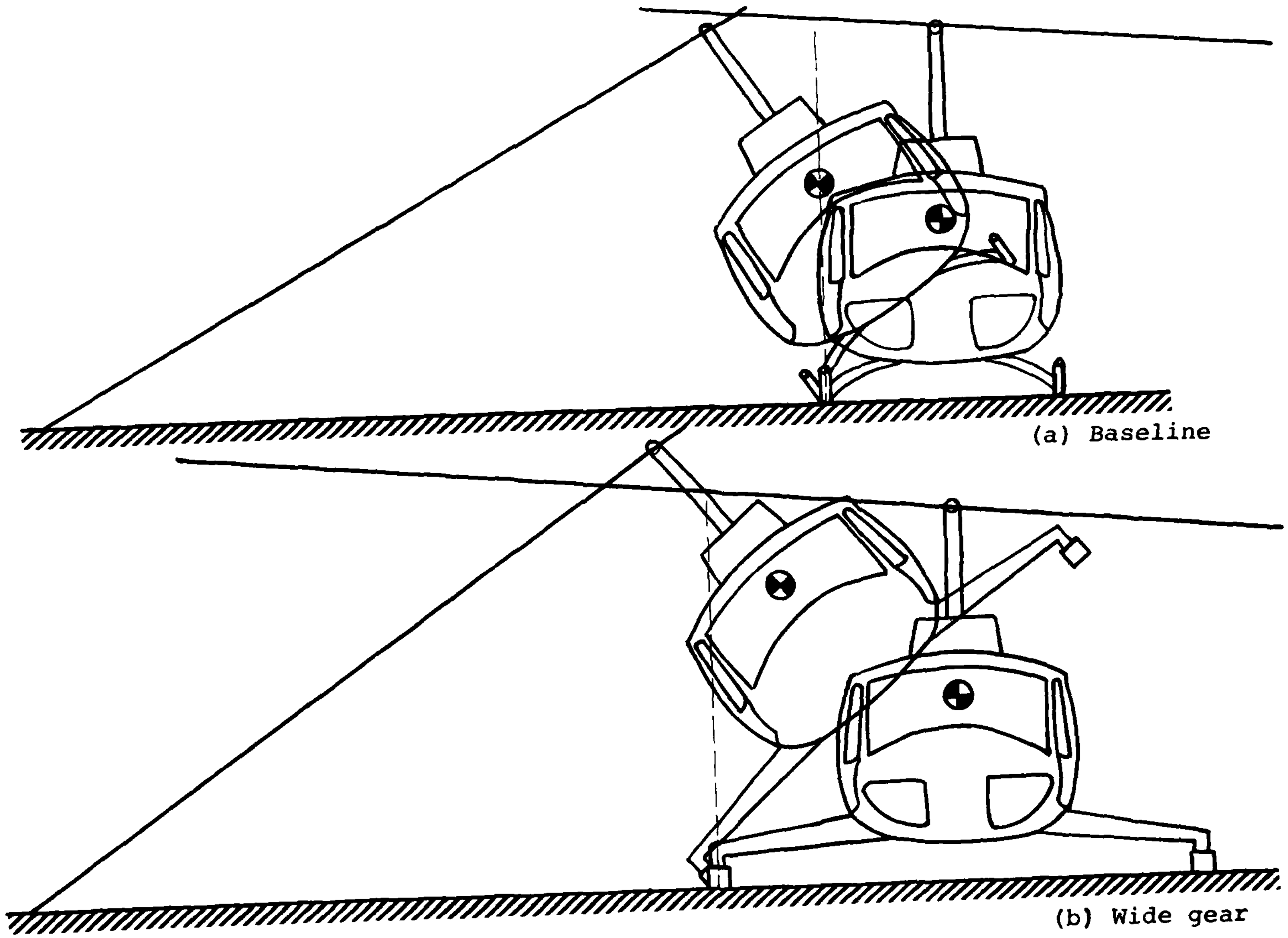


Figure 29. Wide landing gear roll resistance.

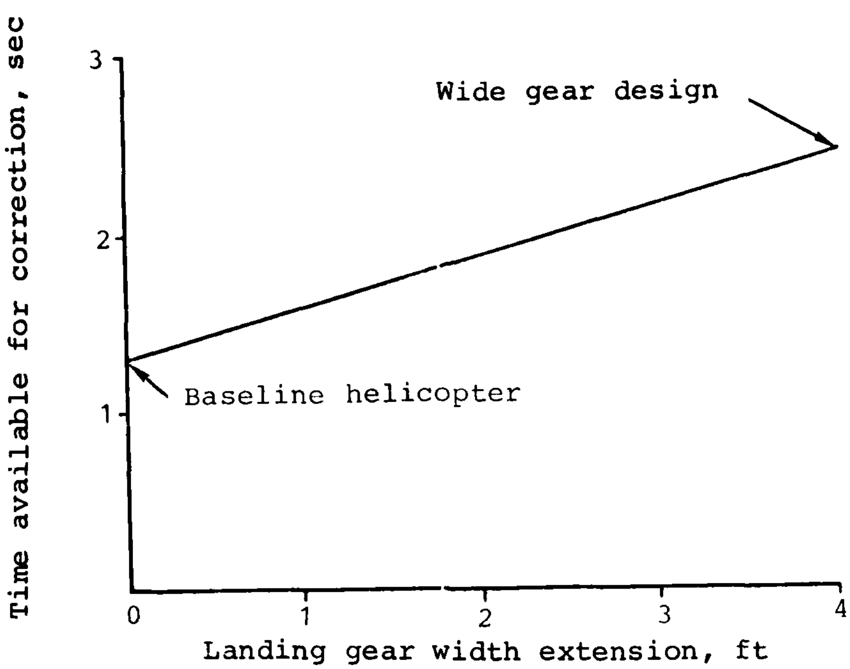


Figure 30. Recovery time vs landing gear width.

5.1.2.2 Wings. Wings on helicopters can also provide a structural pivot point that is outboard of the fuselage. A low wing is better than a wing mounted high on the fuselage due to the wing tip contacting the ground sooner (e.g., less aircraft roll). Experience has been excellent on the AH-1 stub wings in preventing rollover and canopy ground contact. Future helicopter designs should consider crushable wings for lateral energy attenuation in lieu of crushable fuselage sides.

5.1.2.3 Winged Landing Gear. Combining the rollover prevention characteristics of the wing and a wider landing gear can provide some interesting concepts. During a rollover, the present attack helicopter will pivot about the skid until wing tip contact is made. If a main wheel gear were installed outboard at the end of the wing, the resistance to rollover would be increased. The main gear could be made retractable by pivoting it outboard to form an extension of the wing as shown in Figures 31 and 32. This concept could have excellent lateral stability to prevent a rollover accident.

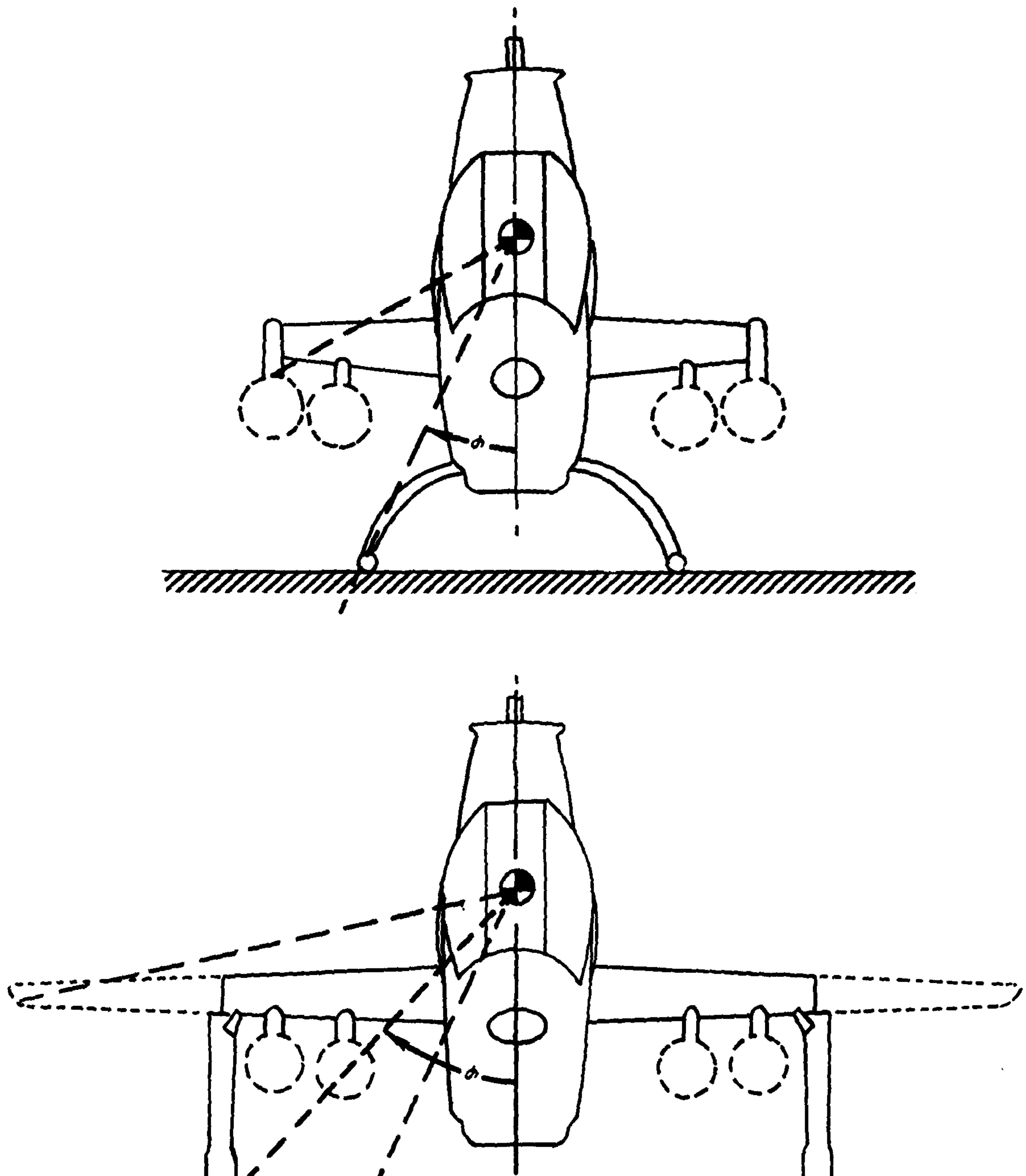


Figure 31. Roll resistance effect of wing-mounted wide landing gear.

(a) Gear up

(b) Gear down

Figure 32. Model AH-1 winged/wheeled landing gear concept.

Figure 33 shows that a variation of this concept would be to leave the wing extension rigid and only lower the landing gear. This concept would allow the wing tip to remain outboard at all times, and also provide a crushable structure for a lateral impact regardless of landing gear position.

5.1.2.4 Deployable Outriggers. A mechanical extension of the pivot point is possible when a rollover accident is imminent. This could be achieved by the quick deployment of structural outriggers as shown in Figure 34. Such outriggers could be normally stored behind the crosstubes to minimize air resistance. The outriggers could be automatically deployed by the DRPS when a rollover is in process.

The concept shown in Figure 35 would pivot the outriggers about the skid tube. Pyrotechnic gas actuators, similar to the AH-1 wing stores jettison devices, could be used to quickly deploy the outriggers when required. Referring to Figure 35, the sequence could include:

- DRPS senses a lateral rollover condition beyond an established threshold
- DRPS sends fire signal to pyrotechnic cartridge (A)
- Gas cylinder actuator (B) within the skid tube retracts piston (C) pulling cable (D) around pulleys and through a hole in the skid tube
- Since cable (D) is attached to the outrigger at (E), the outrigger will rotate outboard
- One-way spring-loaded ratchets (F) prevent the retraction of the outrigger and transfer the rollover loads to the skid tube (G).

A variation of the concept shown in Figure 35 is to mount the pivot tube for the outrigger above the existing skid tube (Figure 36). This concept could be retrofitted to existing skid gear. This concept would function similar to the previous concept, except that the pyrotechnic gas actuator would be installed inside the outrigger. Since the cable end opposite from the actuator is attached to the skid tube, firing of the actuator would pull the outrigger into the deployed position. The same ratchet approach would maintain the outrigger in the deployed position.

Pivoting an outrigger from the fuselage belly can also provide lateral rollover protection. On the baseline helicopter, the

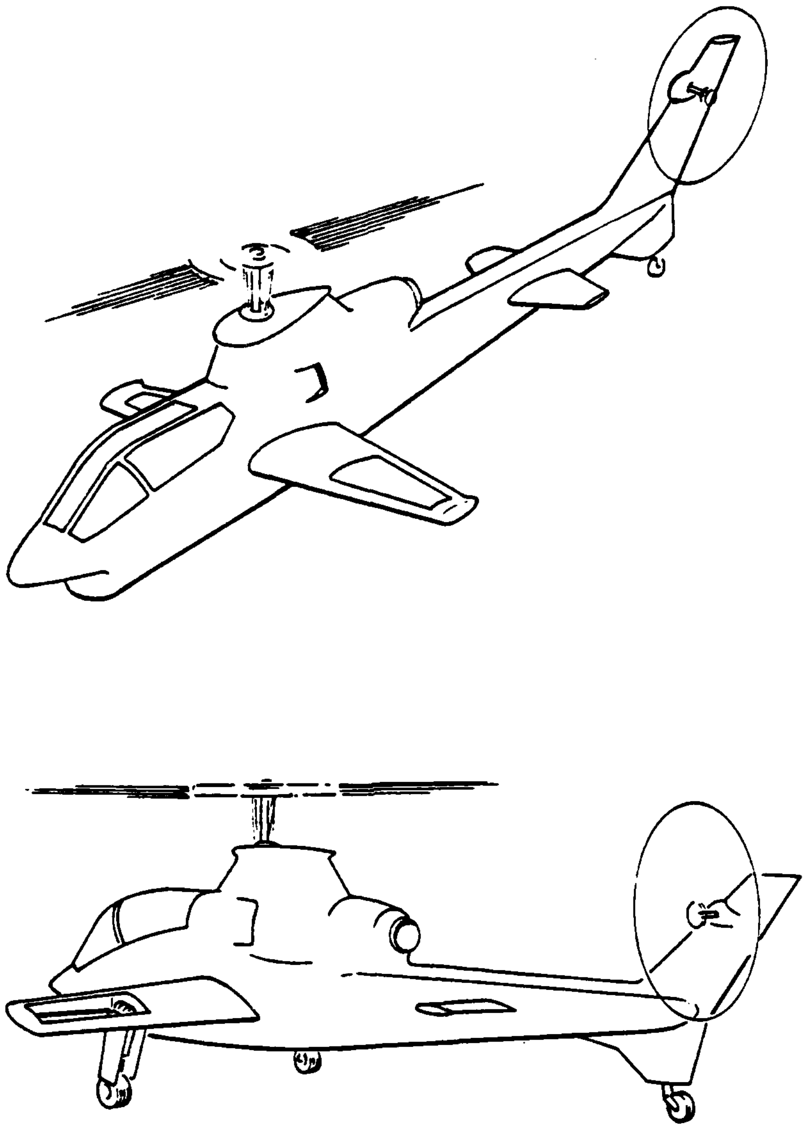
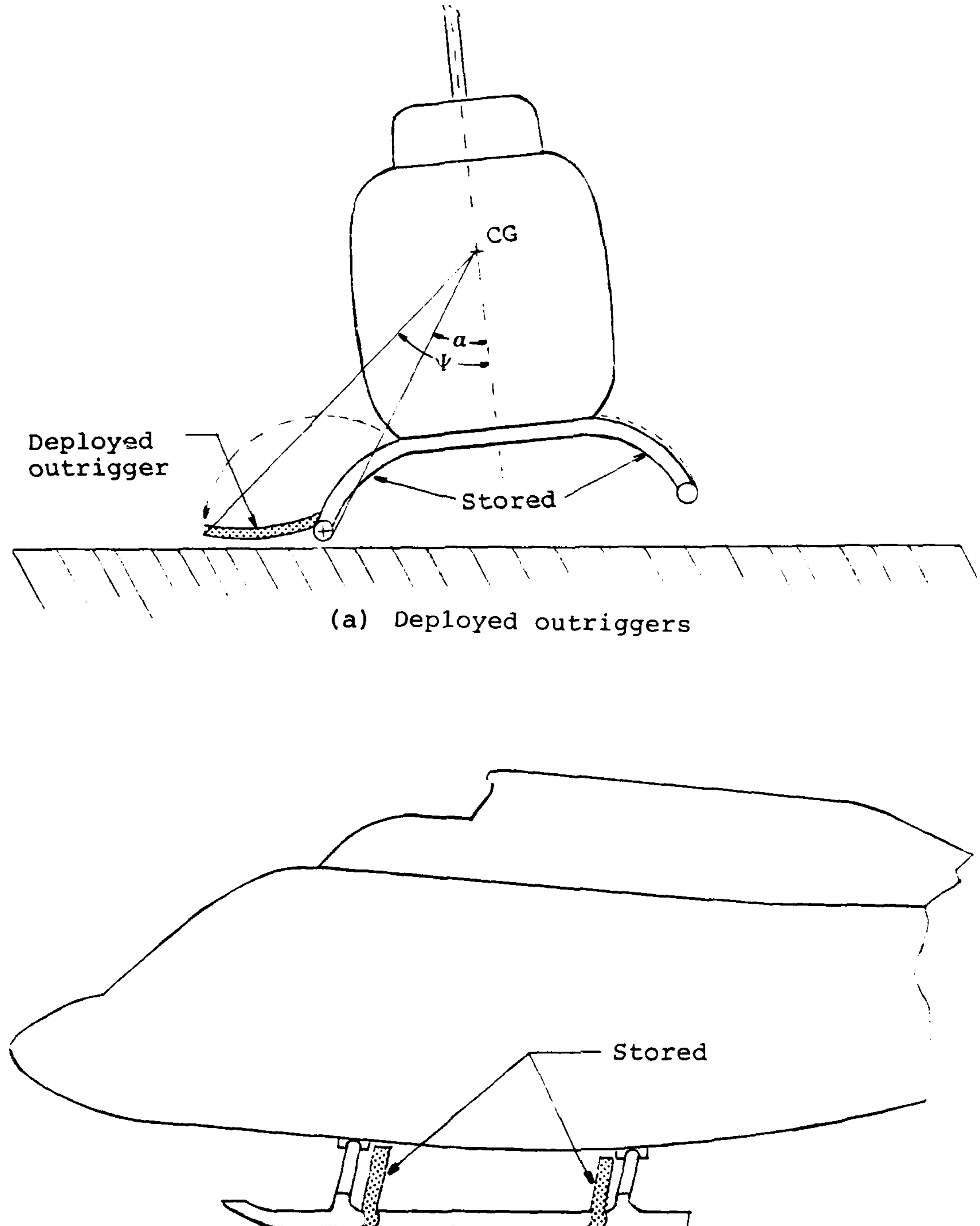


Figure 33. Extended wing/wheeled landing gear concept.



(a) Deployed outriggers

(b) Stored outriggers

Figure 34. Deployable outrigger concept.

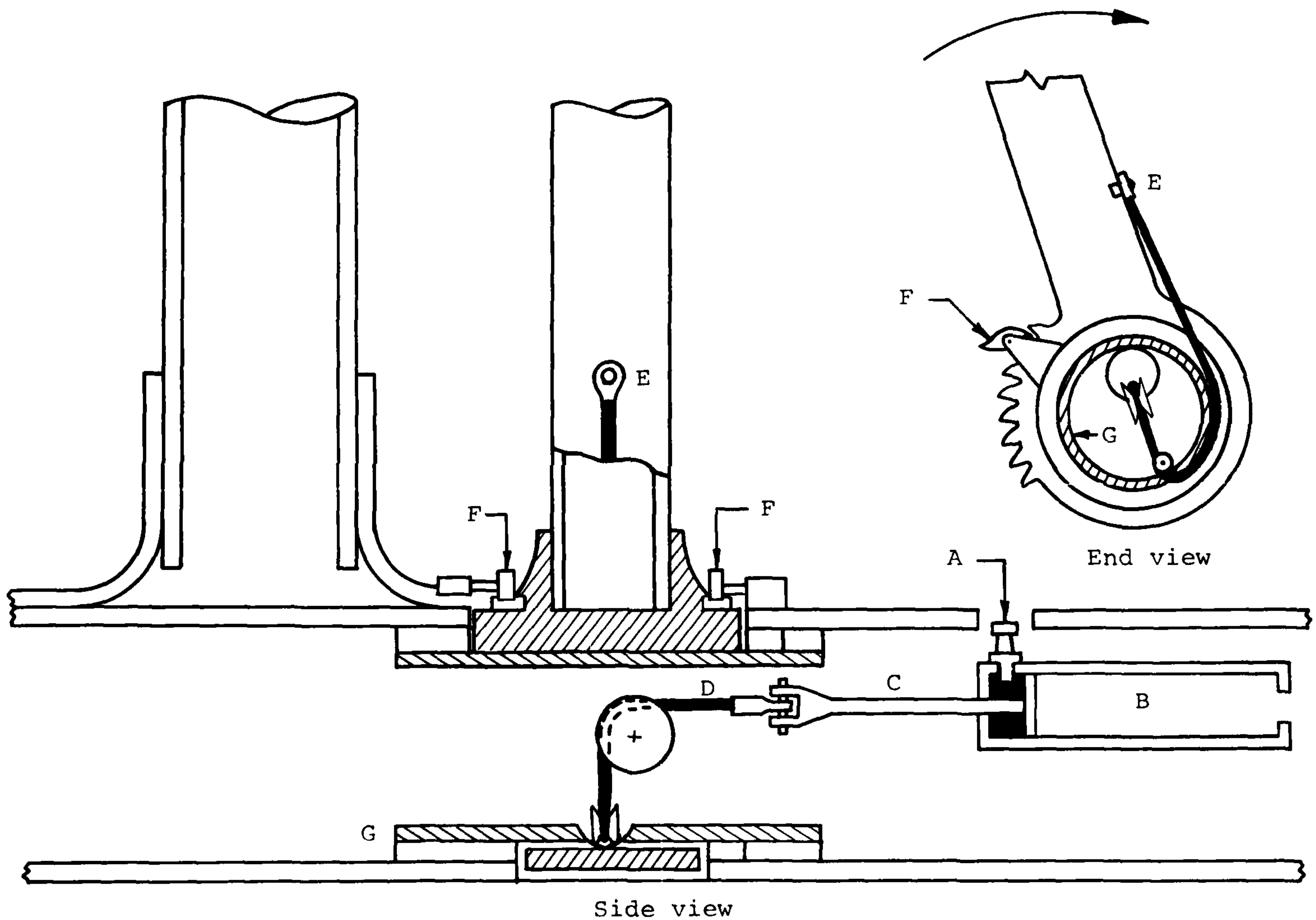


Figure 35. Deployable outrigger pivoted about skid tube.

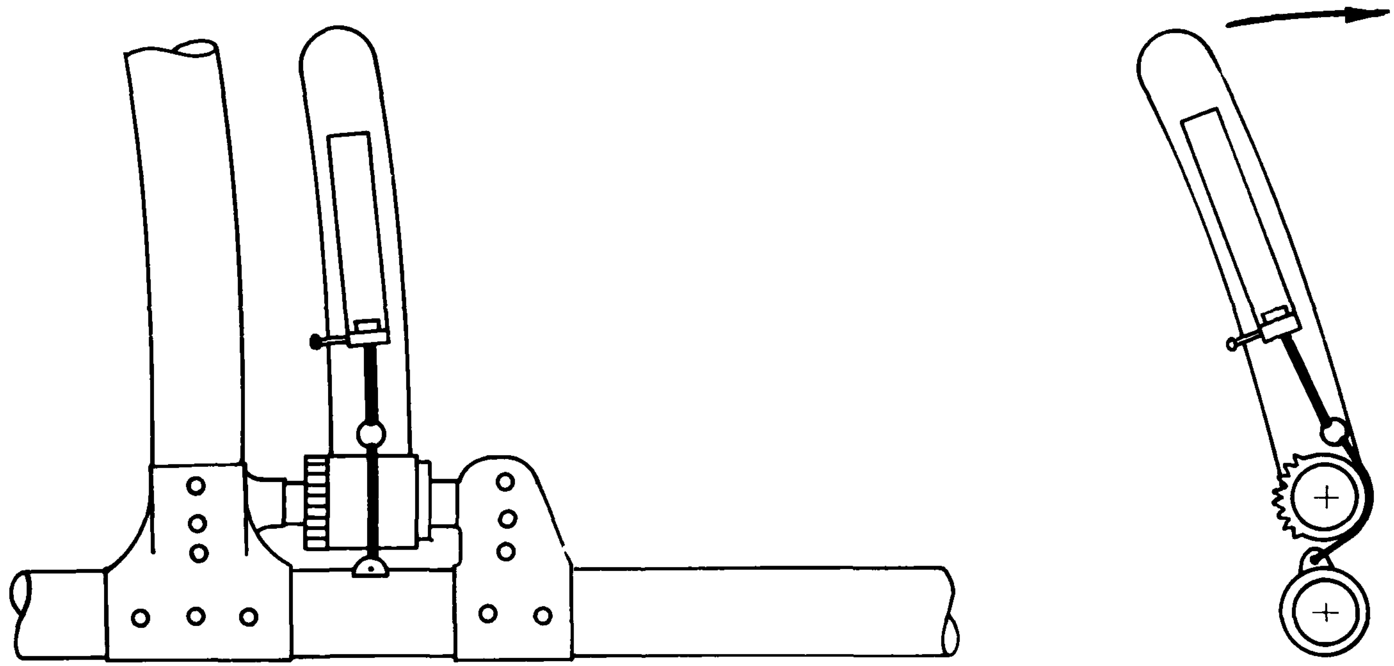


Figure 36. Deployable outrigger mounted above skid tube.

outrigger arm could be attached just aft of the forward crosstube. The outrigger in the stowed and deployed positions is shown in Figure 37. Upon signal to activate from the DRPS, the pyrotechnic gas actuator (A) will drive the outrigger arm (B) to the deployed position where it would be latched in place. During this deployment, the arm (B) would pull out a stowed lanyard from the aft crosstube to skid tube attachment (C). In the deployed position and ground contact at the end plate, the outrigger arm can crush the saddle mount to absorb energy.

5.2 PROTECTION DURING ROLLOVER

If a rollover accident cannot be avoided, then protection during the crash should be provided. Considering the results of the accident analysis of Section 2, lateral rollover protection could be improved by using the concepts described below.

5.2.1 Transmission Retention

Retention of the transmission pylon during a rollover accident is desirable for two reasons. First, a severe transmission detachment could permit the transmission itself or the attached rotor system to enter the occupiable area. Second, ground contact with the roof and the resulting livable volume reduction is reduced because the transmission pylon will carry much of the load in the inverted position. The AH-1G transmission and mounting structure (Figure 38) was analyzed to determine a means of improving transmission retention during a crash and to determine the sensitivity of weight due to these improvements. The following design criteria for three strength levels as defined by static load factors were investigated.

- Present AH-1 (Reference 16)
- MIL-STD-1290 (Reference 1)
- 80 percent of MIL-STD-1290 loads

5.2.1.1 Design Criteria. Three levels of design criteria were used to determine the weight sensitivity due to changing the static load factors. It should be noted that the strength of a structure for a given static load factor may or may not represent the capability of the structure during dynamic

[16]Asplund, E. M., et al., BASIC STRUCTURAL DESIGN CRITERIA FOR THE AH-1G, AH-1Q, AH-1R, AH-1S TACTICAL HELICOPTERS, Technical Reprt 209-099-050 (Revision D), Bell Helicopter Textron, Fort Worth, Texas, 10 April 1978.

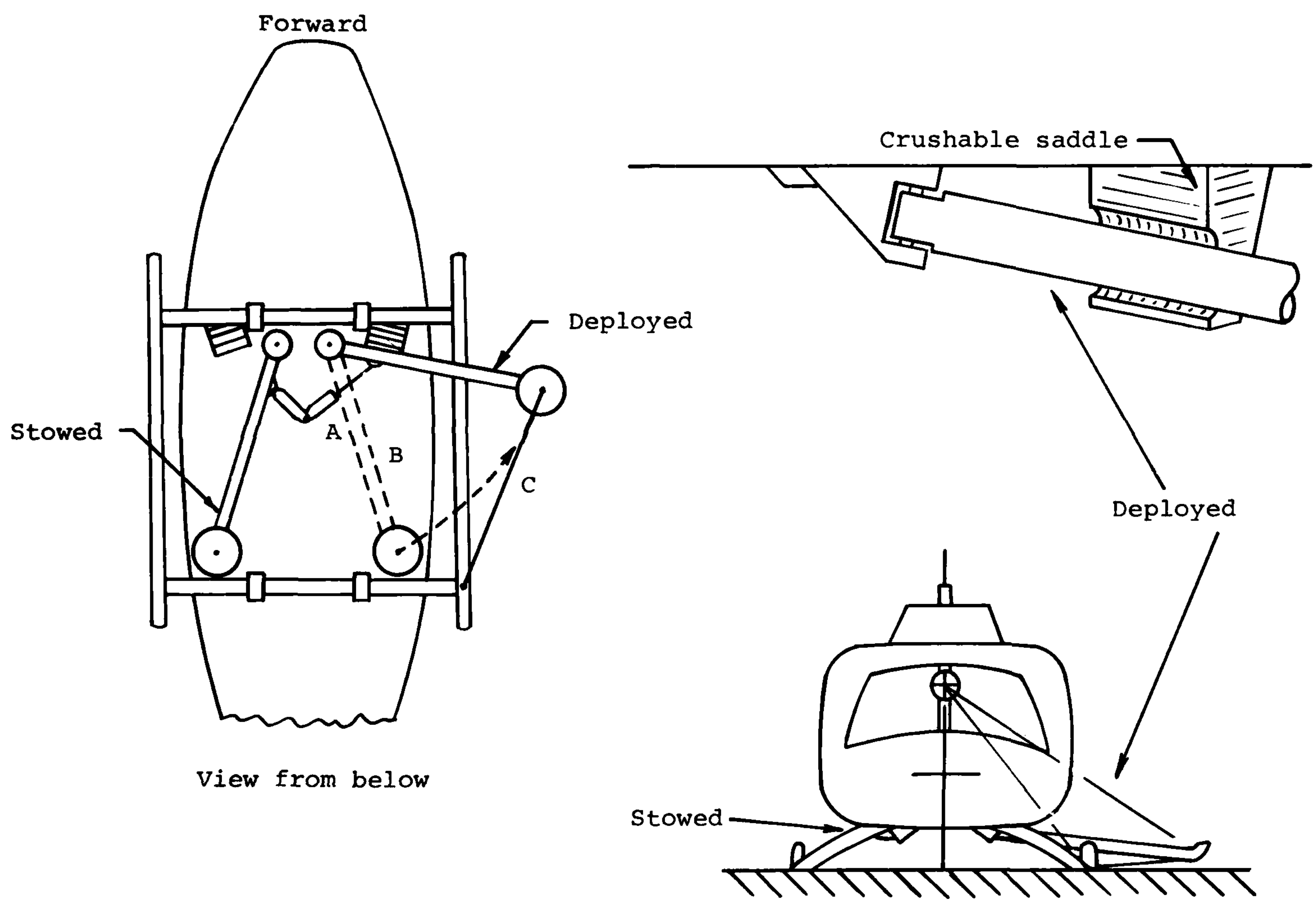


Figure 37. Deployable outrigger mounted to fuselage.

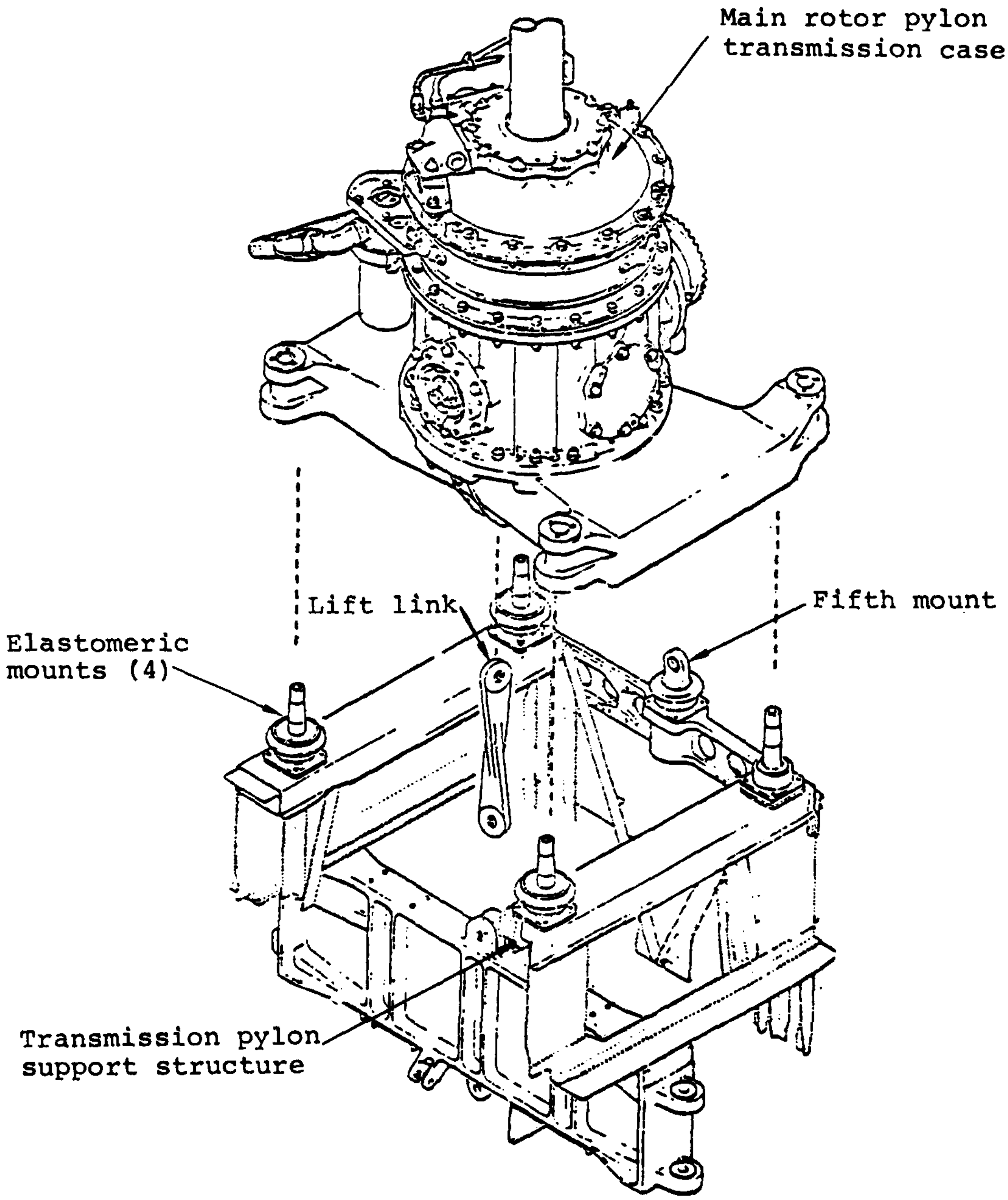


Figure 38. Model AH-1 transmission and mounting.

loading. Many variables are involved during dynamic loading and their investigation is beyond the scope of this study. Accordingly, no attempt has been made to correlate static load factors to dynamic loads incurred during an actual crash. The static load factors that are used in the design of the existing AH-1G transmission and its mounting structure are shown in Table 10.

TABLE 10. MODEL AH-1G TRANSMISSION AND PYLON SUPPORT STATIC LOAD FACTORS* (Reference 16)

Direction	Transmission	Pylon Support
Longitudinal (N_x) (Forward)	8G	15G
Lateral (N_y)	±8G	± 5G
Vertical (N_z) (Down)	8G	15G

* Applied separately

Note that the load factors for the design of the pylon support and the transmission and pylon areas are different. This anomaly would suggest that during a crash the transmission would fail prior to the pylon support area. In reality, both the transmission and pylon support area have experienced crash-induced failures that have caused the pylon to break loose. This suggests that in addition to the use of static load factors, other criteria are needed. It is apparent that failure mechanisms, other than transmission deceleration loads, are involved during a crash. For instance, a blade strike transmits a torsional and bending moment to the pylon that can be severe enough to damage this area.

It should be noted that a load factor is used only as a design point; the actual capability, considering the effects of the surrounding structure, will always be somewhat different. As an example, the actual capability of the existing transmission and support structure is shown in Table 11.

TABLE 11. MODEL AH-1G TRANSMISSION AND PYLON SUPPORT CALCULATED STATIC LOAD FACTORS*

Direction	Transmission	Pylon Support
Longitudinal (N_x) (Forward)	8G	15G
Lateral (N_y)	±8G	±13.9G
Vertical (N_z) (Down)	138G	271G

* Applied separately

Comparing Tables 11 and 12, it is apparent that the longitudinal load condition produces the maximum internal forces within the transmission and pylon support structure. Thus, the capability of the pylon support structure in the lateral and vertical direction, and the transmission in the vertical direction are stronger than the static load criteria would indicate.

The static load factors from MIL-STD-1290 are shown in Table 12. The loads differ from those used to design existing aircraft in two ways - the magnitudes are greater and they are applied asymmetrically as well as symmetrically. Of the conditions shown, the asymmetrical load cases will control the design of the transmission and the pylon support structure, since the forces tend to concentrate on the corners of the structure.

TABLE 12. MIL-STD-1290 TRANSMISSION AND PYLON SUPPORT STATIC LOAD FACTORS

Direction	Symmetrical*		Asymmetrical**	
Longitudinal (N_x)	±20G	±20G	±10G	±10G
Lateral (N_y)	±18G	0	± 9G	±18G
Vertical (N_z)	+20/-10G	+10/-5G	+20/-10G	+10/-5G

* Applied separately
** Applied separately

Design criteria differing from MIL-STD-1290 were studied to determine the sensitivity of structural weight to design load factors. These criteria (Table 13) were derived by multiplying the load factors of MIL-STD-1290 by 0.8. The asymmetrical load cases again will control the design of this AH-1G structure. Two design conditions (N_x8, N_y14, N_z-4, and N_x-8, N_y7, N_z16) will produce internal forces in the transmission that exceed all of the other conditions of the alternate criteria. In addition, these load cases will produce forces that also exceed 13 out of the 18 conditions specified by MIL-STD-1290. Thus, 72 percent of the load conditions specified by MIL-STD-1290, including all of the symmetrical conditions, can be satisfied by designing for these two alternate criteria cases. Since each aircraft structure is different, each model should be analyzed to determine which criteria are driving its design.

TABLE 13. ALTERNATE TRANSMISSION AND PYLON SUPPORT STATIC LOAD FACTORS

Direction	Symmetrical*		Asymmetrical **	
Longitudinal (N_x)	±16G	±16G	±8G	±8G
Lateral (N_y)	±14G	0	±7G	±14G
Vertical (N_z)	+16/-8G	-8/-4G	+16/-8G	+8/-4G

* Applied separately
** Applied simultaneously

5.2.1.2 <u>Strengthen Transmission and Mounting</u>. The present AH-1G transmission transfers all crash loads through the transmission casings. Therefore, an increase in the transmission crash load-carrying capability can be accomplished by either increasing the thickness or the casings, or by providing external reinforcement between the transmission and support structure. Accident photographs indicate that failure of the transmission assembly during a crash impact generally has occurred at one of two locations: the lower case near the attachment lugs or the joint between the lower case and the bevel gear case. At the latter location, some failures have occurred due to the tension loads in the bevel gear case, while others are due to the failure of the studs. Therefore, the concepts will be directed toward improving these areas of the transmission.

The simplest and most direct way to improve the transmission retention strength is by locally increasing the wall thickness of the bevel gear and lower cases. It is estimated that if the MIL-STD-1290 criteria are to be satisfied by this method, an approximate weight increase of 90 pounds to the existing transmission would be required. The weight increase was calculated by a comparison between the transmission cases of the Models AH-1T and AH-1G. This comparison is possible because the bending moment on the AH-1T transmission case for its 12g forward crash load condition is comparable to the bending moments applied to the AH-1G when MIL-STD-1290 criteria are used.

Using the alternate criteria suggested in Table 13, the anticipated weight increase would be about 67 pounds. This transmission weight estimate was derived by comparing the loads on the case with the most demanding asymmetrical loading.

A second concept for improving the transmission retention strength by distributing a portion of the load external to the case is shown in Figure 39. This bipod concept redistributes a portion of the load around the bevel gear case and lower case by attaching to the ring gear case and the corners of the pylon with support tubes. Only the left side assembly is shown in the figure so that the interference with the oil filter on the right side can be noted. To use this concept, the oil filter, the swashplate spring, and some switches on the right aft side of the transmission would have to be relocated. The bipod concept would require four fittings on top of either side to attach the tubes to the ring gear case. The loads in the bevel gear and lower cases are relieved by providing the additional load path through the bipod support struts, thereby increasing the capability of the transmission unit.

Designing to the MIL-STD-1290 criteria will necessitate an increase in the size of the mounting bolts that tie the transmission into the pylon support isolation mounts for either concept. A limiting wall thickness might occur in this area due to the increased hole size and the bending that occurs across the lugs. This condition may also require a redesign of the lower case regardless of the concept used.

Some additional considerations that must be resolved during the development of the bipod concept include:

- An analysis of the heat transfer due to the introduction of additional components and its effect on the functioning of the transmission

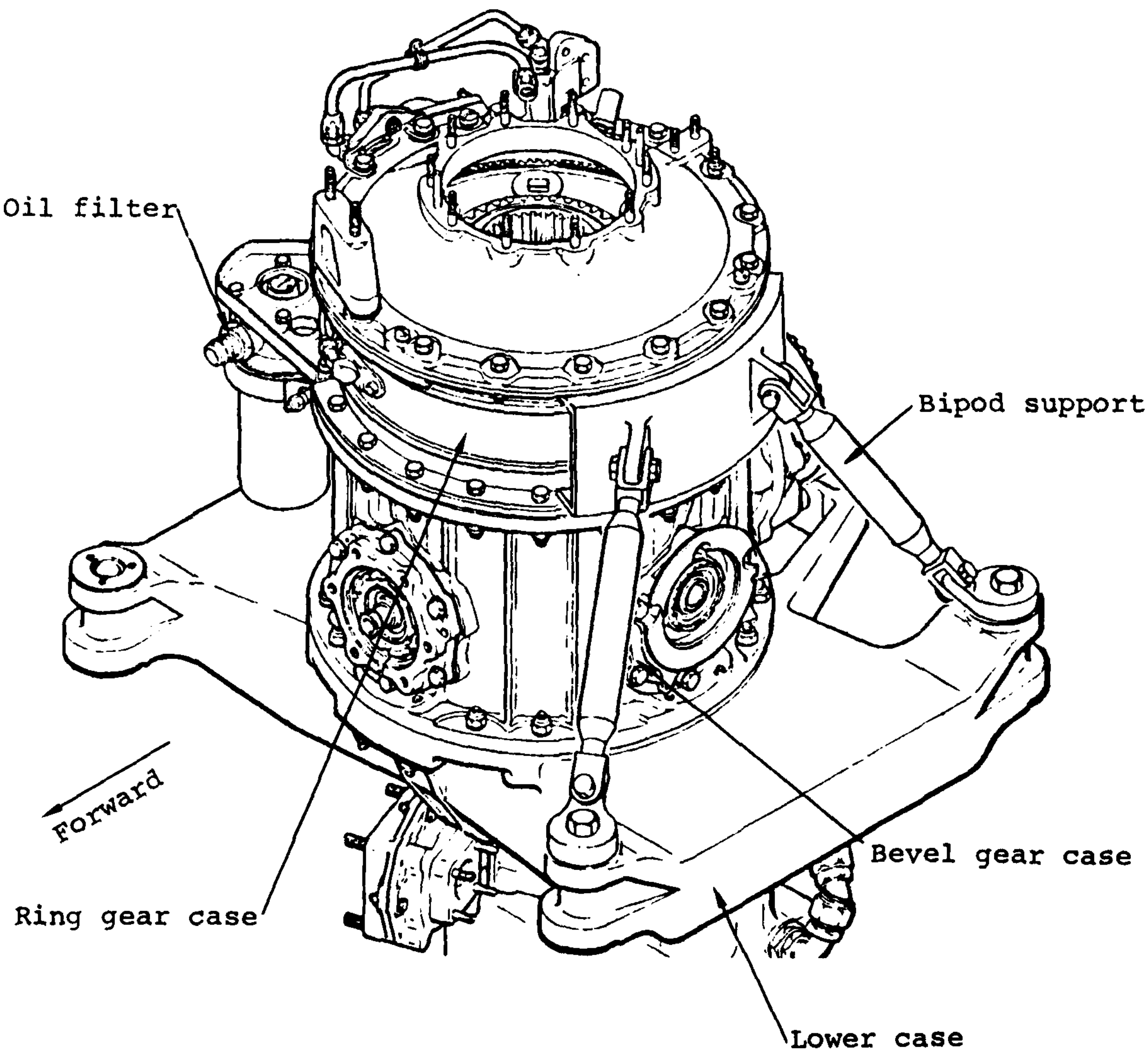


Figure 39. Transmission bipod support concept.

- An investigation of the thermal mismatch between the case and bipods that is created by the different materials

- A study of the stiffness discontinuity of the ring gear case created by the added upper fittings to the left- and right-hand sides

- A potential increase in the size of the isolation mount bolts

The estimated transmission weight increase for the bipod concept, assuming no change to the lower case, is 25 pounds using MIL-STD-1290 criteria; 18 pounds if the alternate criteria are applied.

To be effective, the increased crash load-carrying capability of the transmission must be accompanied by a corresponding increase in the pylon mounting strength. Increasing the sheet metal thicknesses of the pylon will increase the strength of the structure. The increased capability of the pylon support structure can be obtained for an additional 23 pounds using MIL-STD-1290 criteria, or 15 pounds if the alternate criteria are applied.

The total weight increase required to satisfy the MIL-STD-1290 criteria would be 113 pounds for the redesigned casing concept and 48 pounds for the bipod concept. Using the alternate criteria, the weight increases would be 82 pounds and 33 pounds, respectively, for the casing and bipod concepts. These weight increases do not account for additional fuel required to maintain range requirements or increased rotor and power requirements to maintain performance.

5.2.2 Main Rotor Flapping Restraints

The main rotor hub spring presently being investigated under contract DAAJ02-77-C-0064 (Reference 17) has the potential to minimize mast fracture due to severe flapping from blade strikes. The nonlinear elastomeric hub spring has been successfully flight tested to reduce blade flapping. A small amount of flapping is permitted by the shear pads, as shown in Figure 40. When flapping exceeds 4 degrees, the compression

[17] CRITERIA AND CONCEPT FOR IMPROVED UH-1 MAST BUMPING SAFETY MARGIN, Contract DAAJ02-77-C-0064, Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia.

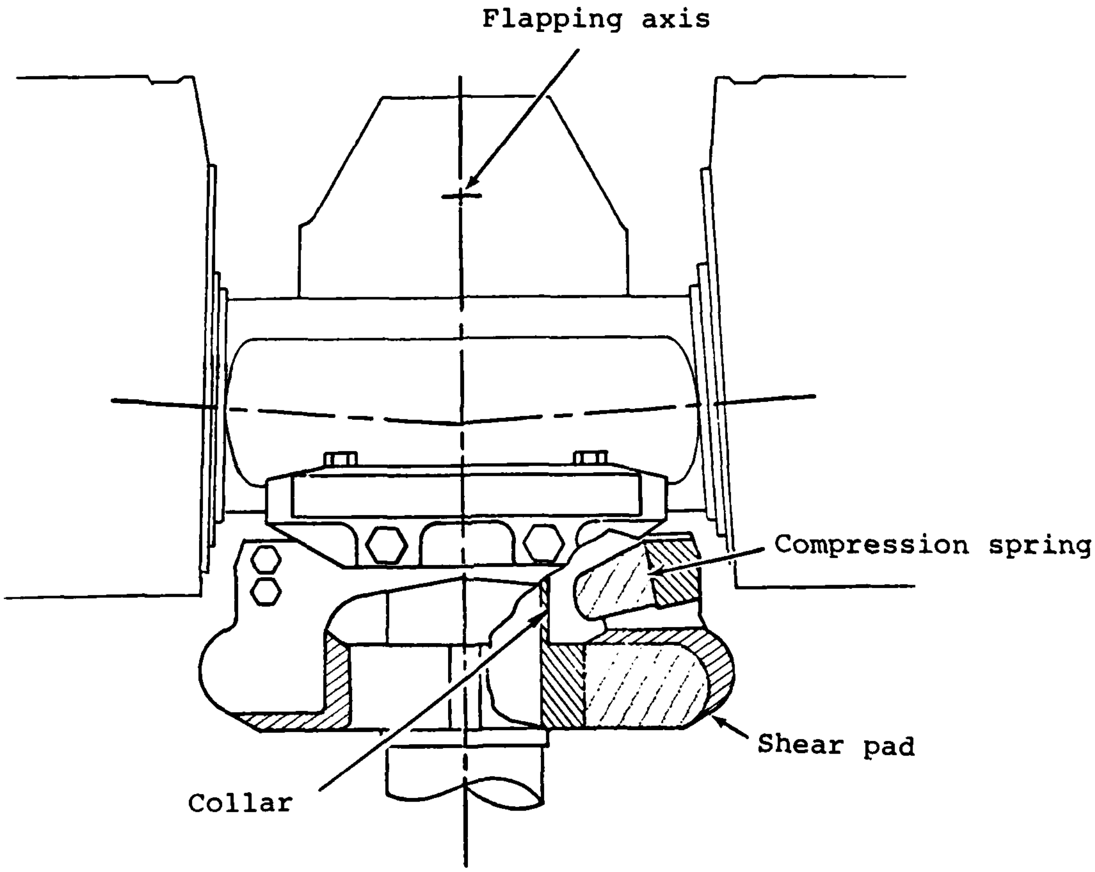


Figure 40. Model UH-1H nonlinear hub spring.

spring contacts the collar around the mast. The stop contact area is increased about ten times over the present stop area. The hub spring will reduce the likelihood of a main rotor hub-to-mast separation due to extreme blade flapping.

5.2.3 Main Rotor Crash Load Limiters

In-plane blade strike crash loads transmitted to the mast contribute to pylon failures. Therefore, if these short-lived, high crash loads can be minimized, their detrimental effect on pylon displacement can be reduced. Several concepts to limit the crash loads are given. The approach is to provide a fuse or load limiter to allow transfer of loads only up to a non-harmful level. These limiters could be placed in several places between the blade tip and the main rotor mast.

5.2.3.1 Crushable Blade Tip. The blade tips can be made frangible to crush upon blade impact. Deforming the tip should be as controlled as possible. For example, if a frangible tip with tip weight fractures and leaves the blade, the resultant main rotor centrifugal unbalance may cause severe pylon damage. Therefore, blade tips should retain their weights during the blade strike. A replaceable frangible blade tip concept (from Reference 18) is shown in Figure 41.

5.2.3.2 Frangible Rotor Blade. For future main rotor blade design, it may be possible to construct a blade that can accept localized destruction during a blade strike such that harmful blade strike loads are not transmitted to the mast. The blade should progressively fail inward starting at the blade tip. Use of filament composite materials could accept the failure of the resin material, yet retain some of the load-carrying capability of the fibers. Means of blade balance weight retention should be included. Composite main rotor blades presently being developed for the Army, or scale main rotor testing, could be used to evaluate this concept.

5.2.3.3 Frangible Drag Brace. Most of the U.S. Army helicopter fleet use a drag brace to adjust the spanwise balance of the main rotor. The drag brace attaches the trailing edge of blade to the blade grip, as shown in Figure 42(a). If the drag brace were made such that it would crush, it could allow the blade tip to stop over a longer time period (i.e., lower strike loads transmitted to the hub). A frangible drag brace

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[18] Gupta, B. P, HELICOPTER OBSTACLE STRIKE TOLERANCE CONCEPTS ANALYSIS, Technical Report 78-46, Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1979, AD A069877.

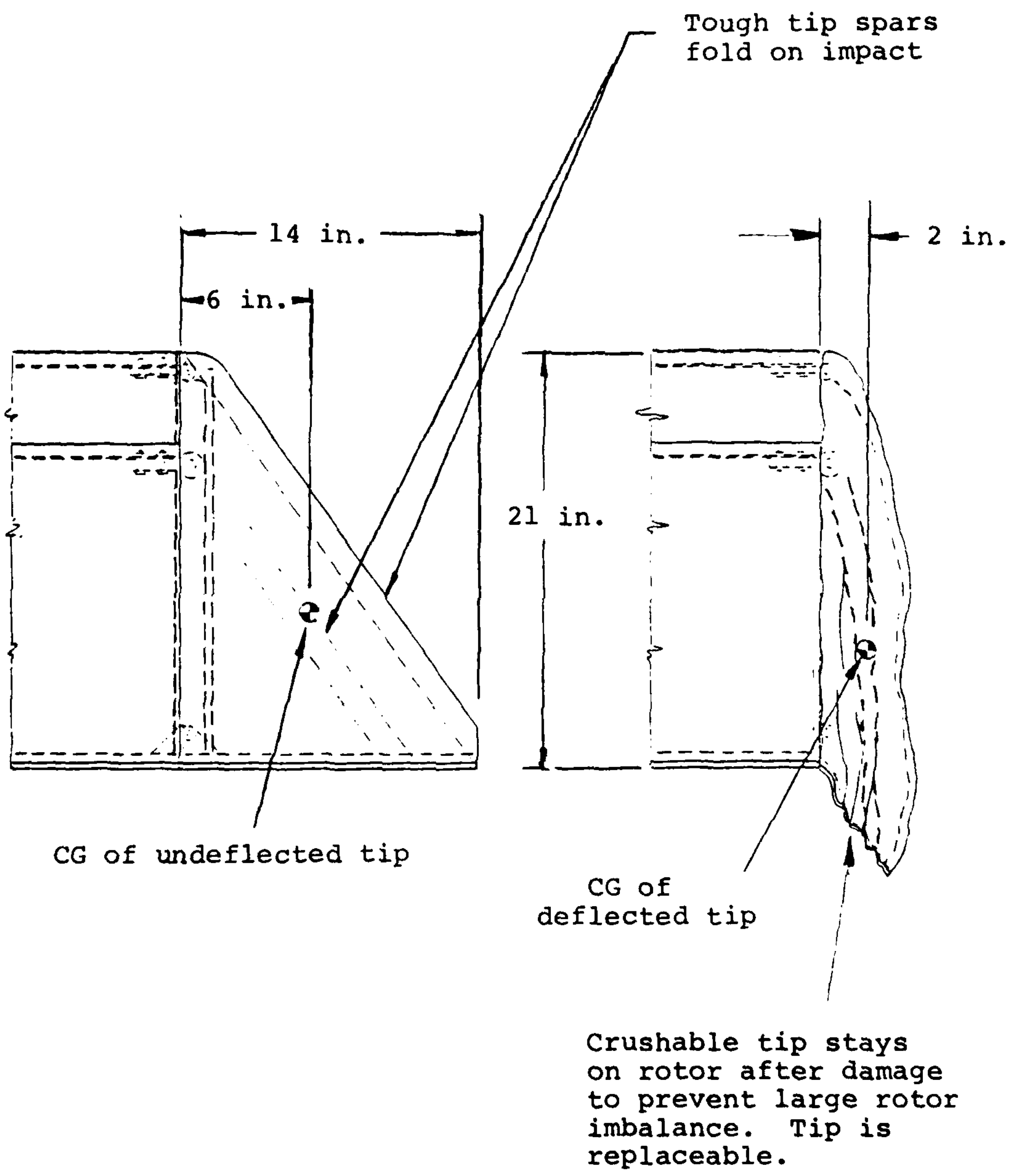
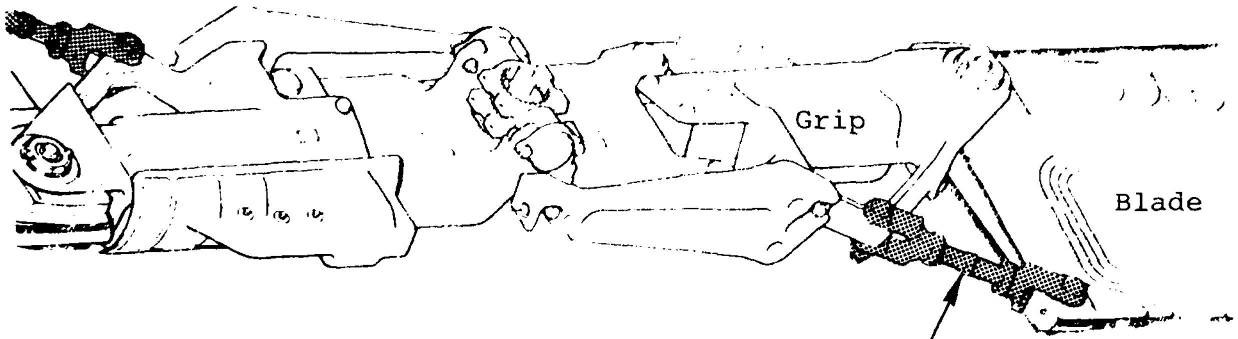
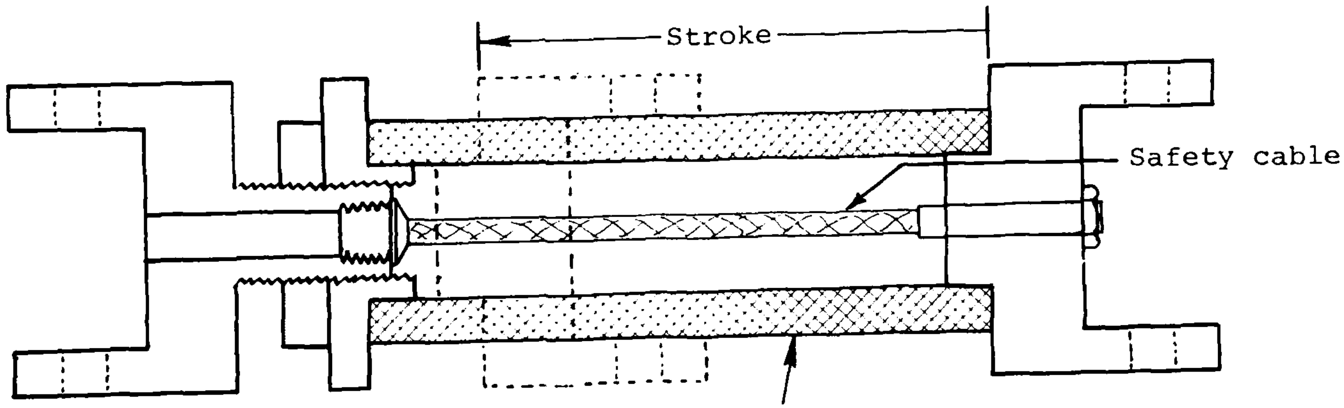


Figure 41. Frangible main rotor blade tip.



(a) Drag brace installation



(b) Drag brace detail

Figure 42. Frangible drag brace.

could include a crushable composite tube as shown in Figure 42(b). Previous testing (Reference 15) on composite tubes for other purposes has shown that they can be excellent energy absorbers. These composite tubes can crush nearly the entire length of the tube between end mountings, as shown in Figure 43.

5.2.3.4 Frangible Lead/Lag Damper. Helicopters with fully articulated main rotors generally use a damper mechanism to allow each blade to independently lead or lag in the plane of rotation. The blade will lag (e.g., blade tip lags behind the hub rotation) when a blade strike occurs that reduces the crash loads transmitted to the hub. The addition of a crushable tube like the frangible drag brace, or any energy-attenuating feature in series with the damper, could further reduce the crash loads transmitted to the hub. In an oil piston damper, an internal bypass valve could provide energy attenuation without a hydraulic lockup.

5.2.3.5 Hub-to-Mast Torque Limiter. The attachment of the main rotor hub to the mast could be used to install a load limiter or torque fuse. One concept would be to divide the main rotor trunnion (teetering rotor) into two concentric rings joined by fuse plugs, as shown in Figure 44. During a severe blade strike, these concentric rings would remain together in the vertical directions but would shear the fuse plugs, thus allowing the blade to lag behind the hub (i.e., lower crash loads transmitted). These fuse plugs could be made of elastomerics, plastics, and even soft metals. This concept is also applicable to tail rotors and fully articulated main rotor hubs.

5.3 COCKPIT STRUCTURAL BLADE STRIKE PROTECTION

To prevent main rotor blade entry into the cockpit is an extremely difficult task due to the conflicting requirement for good pilot visibility. Structural members that can deflect a main rotor blade will have to be large in size, thus restricting the pilot's visibility. A roll cage cockpit, similar to Figure 45, could minimize blade intrusions. Note the large structural beams overhead and on the outboard sides. High-strength windshield posts and door posts that attach the overhead structure to the floor beams provide the remainder of the roll cage.

High-strength deflector beams could be installed forward of the windshield rather than as windshield posts, as shown in Figure 46. Moving the beams further away from the pilot will minimize the pilot visibility restriction. Such external deflector beams could also deflect wires up over the cockpit.

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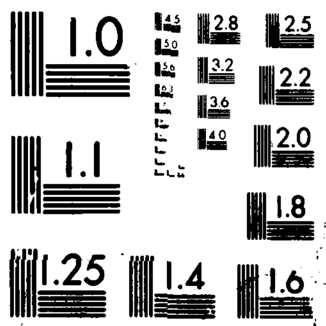

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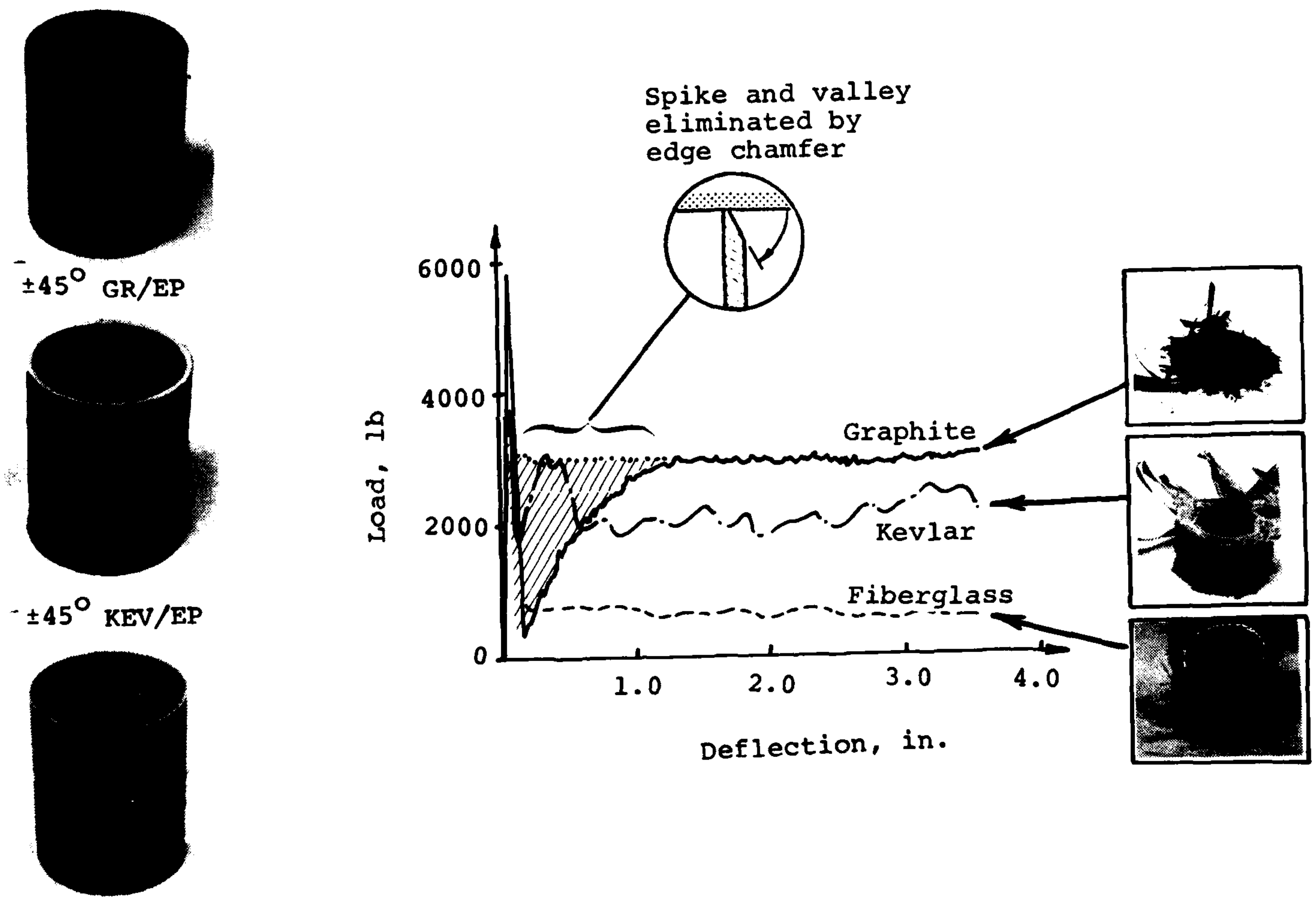

Figure 43. Composite tube energy attenuator testing.

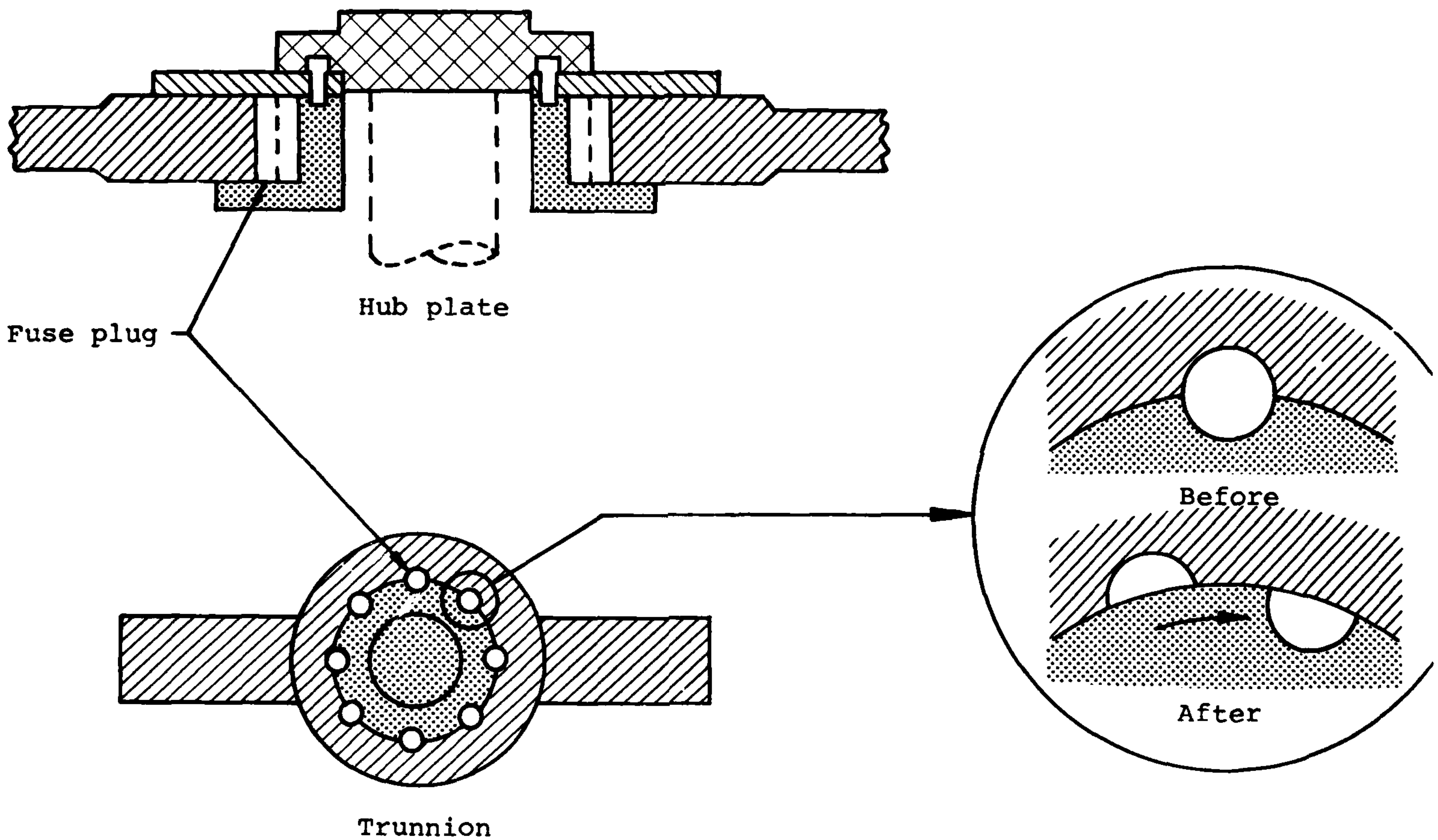

Figure 44. Hub-to-mast torque limiter concept.

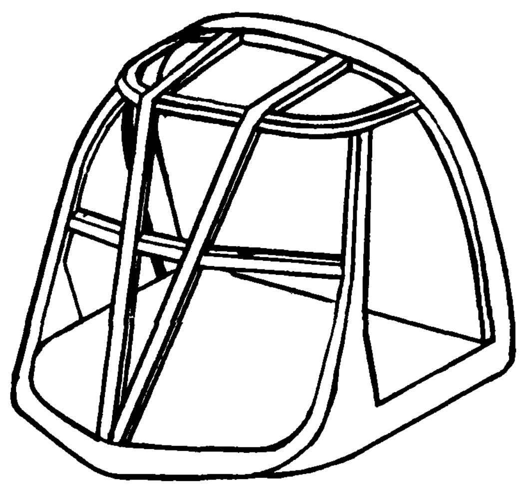

Figure 45. Cockpit structural blade strike protection.

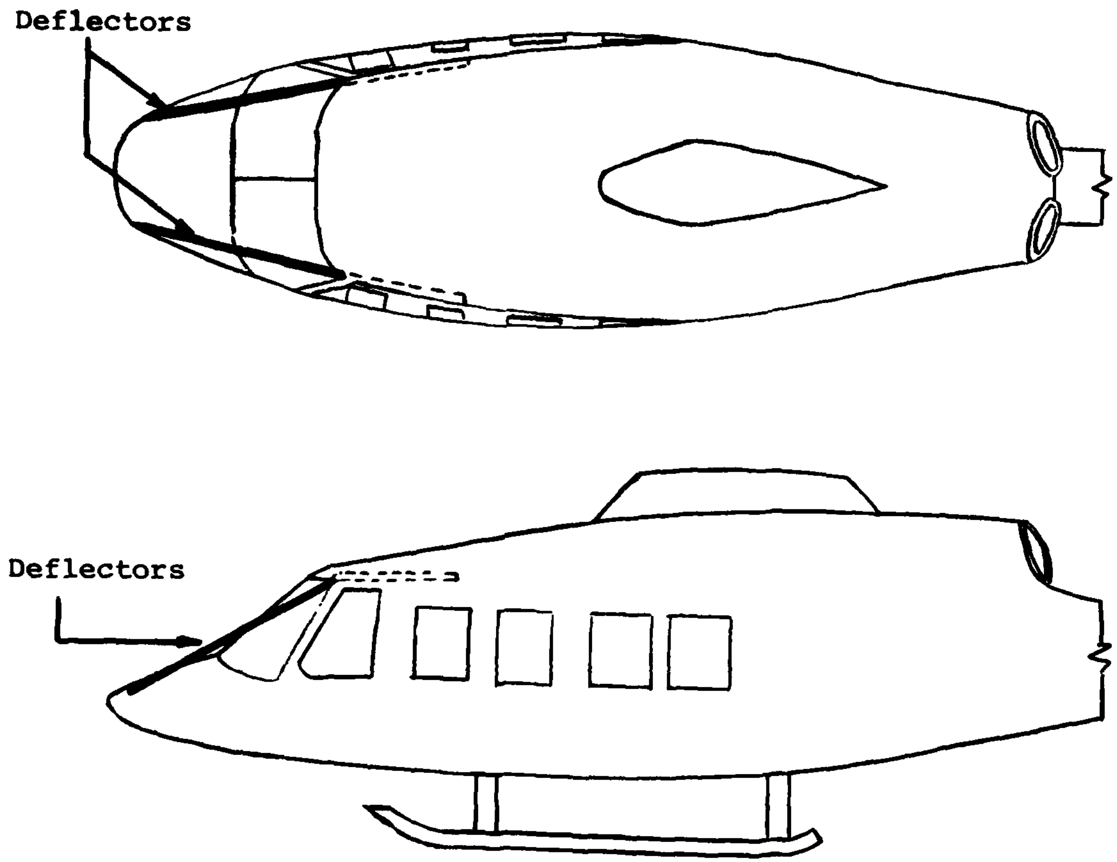

Figure 46. Externally mounted blade strike deflectors.

5.4 SECONDARY IMPACTS

Occupants of aircraft in a crash must not only be protected during the initial impact (e.g., airframe) but also during the secondary impacts (e.g., occupant striking aircraft components). The restraint system holds the occupant's torso in place and should prevent him from striking nearby objects with his head or torso. A considerable amount of work is being done by the military to improve restraint systems. Any resulting restraint improvements will help in all accidents whether a rollover occurs or not. Somewhat unique to a rollover accident is lateral body motion and resulting flailing. Two passive approaches to minimizing this flailing include deployable air bags. Air bags could be stowed in the structure, roof, or on an outboard seat station (Figure 47). Deployment of the air bags could be activated by a "G" switch. Porous air bag material could allow bag deflation after the impact. One item of concern is the hindrance to escape that a deployed air bag might present. The other approach is to mount a small air bag or inflatable head restraint device directly on the shoulder harness. Once activated by a "G" switch, the bag would deploy around the occupant's neck (Figure 48). This inflated collar could then reduce the neck flexing and resulting head motion.

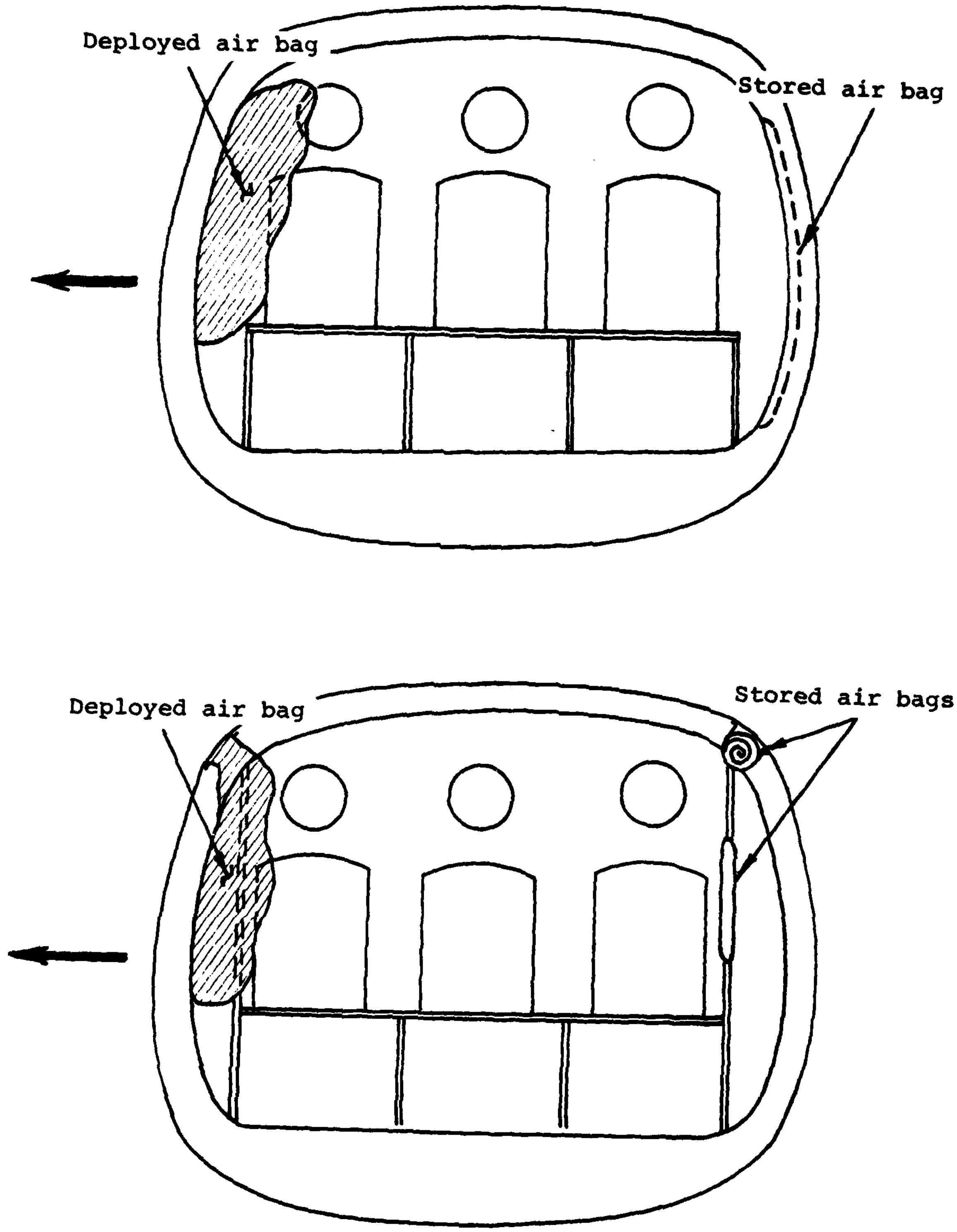

Figure 47. Aircraft-mounted air bag.

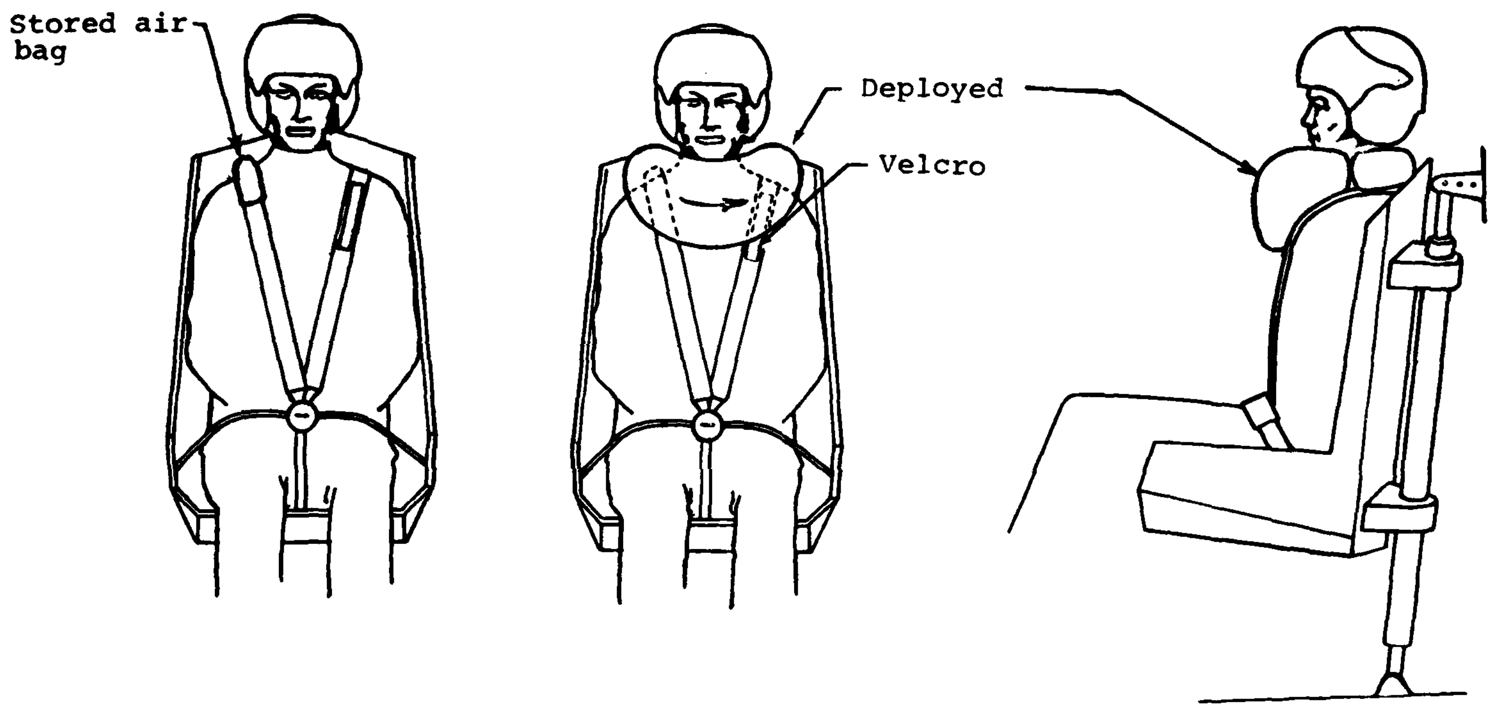

Figure 48. Inflatable head restraint.

6. CONCLUSIONS

Based on the results of this effort, it is concluded that:

- Aircraft damage cost related to accidents involving lateral rollover is a significant part of U.S. Army helicopter fleet life-cycle cost (equivalent to $22.65 per flight hour for the 6-1/2 years considered).
- Major or fatal injuries to occupants in rollover accidents occurred at a lesser rate than for all-cause accidents.
- Rollover accidents generally occur with low airspeeds and sink speeds on hospitable terrain.
- Accident data accuracy and completeness vary drastically. Improved accident information is needed for any further detailed analyses.
- Computer simulation of the dynamic rollover phenomenon indicates that the pilot has a very short time available for making corrective control inputs, the most effective of which is reduction in main rotor thrust (lower collective). In addition to defining the motion problem, computer simulation will be useful in evaluating design concepts for rollover prevention and protection.
- Design concepts that will prevent lateral rollover are technically feasible.
- Design concepts that can provide protection to the crew during lateral rollover are technically feasible.
- Rollover protection and protection can be improved on present helicopters using the concepts identified herein. However, for the best cost effectiveness, these improvements should be incorporated during the conceptual phase of a helicopter design.

7. RECOMMENDATIONS

IMMEDIATE

- Train pilots in recognition/response to rollover to include use of flight simulators with visual clues.
- Incorporate main rotor hub springs into fleet.
- Implement flight/crash data recorders into fleet.

FUTURE

- Design, fabricate, and test dynamic rollover prevention system to include automatic heating control and deployable outriggers. Consider scale model testing.
- Design, fabricate, and test AH-1 transmission bipod concept and blade strike load limiters. Consider scale model testing.
- Extend dynamic rollover simulation to include three dimensions and corrective inputs.
- Develop simulation technique for severe blade flapping. Refine KRASH analysis and add hub loads.
- Investigate wider landing gear and winged/wheel gear.

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